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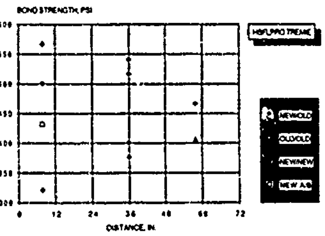

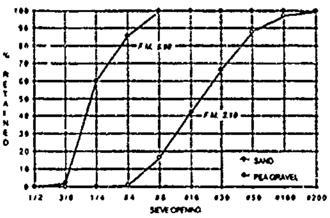

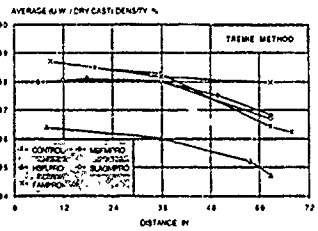

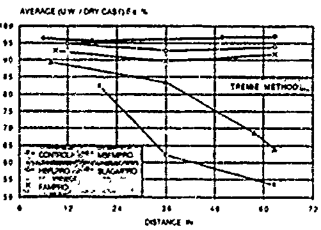

REMR RESEARCH PROGRAM

REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-CS-37

UNDERWATER REPAIR OF CONCRETE DAMAGED BY ABRASION-EROSION

by

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Berkeley, California 94702

December 1991

Final Report

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Problem Area		Problem Area	
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

COVER FIGURES:

1 — Bond strength values along the HSFLPRO-tremie slab.

2 — Aggregate gradation.

3 — Average densities along tremie-cast slabs.

4 — Average compressive strengths along tremie-cast slabs.

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The grinding action of waterborne debris circulating in concrete stilling basins, open channels, navigation locks, and other hydraulic structures can lead to abrasion damage several feet in depth. Damaged areas need to be periodically repaired to ensure the functionality and safety of the hydraulic facility. Traditionally, these repairs have been carried out after dewatering the damaged area; however, such practice can interfere with the operations of the facility and can prove to be very costly. Therefore, it is desirable to carry out the repairs while the damaged portion of the structure is submerged.

Traditional concretes and placement techniques used for massive underwater placements, such as bridge piers, rely on depositing the concrete beneath freshly cast concrete. This technique prevents it from flowing through water where it would segregate and intermix with the surrounding water, resulting in a significant reduction in quality. However, in our case, because of the limited depth of typical abraded scour holes and the need to frequently move the placement device,

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the concrete may have to flow a short distance through water. The objective of this research was to develop concrete mixtures and placement methods to repair typical scour holes underwater.

Guidelines for selecting concrete-making materials and additives were established, and new tests for assessing various properties were developed to complement existing ones. Approximately 70 concretes were evaluated to optimize mixture proportions.

The four most promising fluid concretes and one control concrete were selected to fill small and relatively shallow depressions underwater using the conventional tremie and the proposed inclined tremie methods. Concrete was placed in the laboratory in a test box with the bottom especially shaped to simulate a small scour hole. Surface profiles and in-place mechanical properties of eight underwater-cast slabs and one slab that was cast above water were evaluated to compare concrete mixtures and placement techniques.

Two fluid concretes were developed and used to cast two moderately congested reinforced beams underwater. Field placements were conducted to repair a rough-edged hole measuring 16 by 2.5 by 2.5 ft underwater. Another field experiment was conducted to cast two 22- by 10- by 1.3-ft slabs underwater. In-place concrete properties, proper spacings between discharge points, limitations on dropping concrete in water, and proper batching and mixing sequences were determined.

Stiff, highly washout-resistant concretes which can be dropped a short distance in water and then compacted into place with heavy rollers were developed to repair very thin (6-in.) scour holes. Three underwater compaction trials were conducted to determine in-place properties of the cast slabs and establish optimum concrete lift thicknesses and consolidation efforts.

Methodologies detailing construction procedures were developed, and a database was designed and implemented to facilitate the selection of promising concretes for repairs.

This research shows that concrete structures with scour holes of various depths and sizes can be successfully repaired underwater. Flat and durable surfaces can be secured with in-place compressive strengths exceeding 8,000 psi and relative density values close to 100 percent of control concrete which has been cast and consolidated above water. These concretes and construction procedures can provide economical, safe, and durable repairs to underwater structures.

PREFACE

The work described in this report was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), as part of the Concrete and Steel Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The work was performed under Work Unit 32305, "Techniques for Underwater Concrete Repair," for which Drs. Ben C. Gerwick and Weston T. Hester, University of California, Berkeley, were Principal Investigators. Dr. Tony C. Liu (CECW-EG) was the REMR Technical Monitor for this work.

Mr. Jesse A. Pfeiffer, Jr. (CERD-C) was the REMR Coordinator at the Directorate of Research and Development, HQUSACE; Mr. James E. Crews (CECW-OM) and Dr. Liu served as the REMR Overview Committee; Mr. William F. McCleese (CEWES-SC-A), US Army Engineer Waterways Experiment Station (WES) was the REMR Program Manager. Mr. James E. McDonald, Concrete Technology Division (CTD), WES, was the Problem Area Leader. The work was monitored at WES, SL, by Messrs. Kenneth Saucier (CEWES-SC) and Billy Neeley (CEWES-SC-CG) under the general supervision of Messrs. Bryant Mather and James Ballard, Chief and Assistant Chief, respectively.

The work was performed at the University of California, Berkeley, and this report was prepared by Kamal Henry Khayat in partial fulfillment of the Ph.D. requirements under contract/support agreement No. DACW 39-86-K-0018.

Commander and Director of WES was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

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CONVERSION FACTORS, US CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

US Customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic feet per second	2.831685	cubic metres per second
cubic inches	16.38706	cubic centimetres
cubic yards	0.7645549	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
feet	0.3048	metres
feet per second	0.3048	metres per second
fluid ounces	29.57353	cubic centimetres
fluid ounces per cubic yard	0.038680715	litres per cubic metre
inches	25.4	millimetres
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic yard	0.5932764	kilograms per cubic metre
pounds (mass) per square foot	16.01846	kilograms per cubic metre
pounds (force) per square inch	0.006894757	megapascals
square feet	0.09290304	square metres
tons (2,000 lb mass)	907.1847	kilograms

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9)(F - 32). To obtain Kelvin (K) readings, use: K = (5/9)(F - 32) + 273.15.

CHAPTER ONE

BACKGROUND AND INTRODUCTION

1.0 Background

Open channels, dams, navigation locks, and other vital hydraulic facilities frequently incorporate structural elements of submerged concrete. Due to sharp declines in new construction, existing hydraulic structures should be diligently maintained to enable them to operate beyond their intended service lives and design capacities. Out of the 536 dams and 260 lock chambers operated by the U.S. Army Corps of Engineers in 1985, 60 percent were reported to be over 20 years old and approximately 30 percent were over 40 years old (McDonald et al. 1985).

In a review of 2,018 inspection reports of hydraulic structures, approximately 10,000 cases of deficiencies were identified. Among the types of distress were cracking, spalling, erosion and disintegration. In an effort to identify the primary cause of the observed deficiencies, 17 percent of these cases were further investigated. Among the identified causes of distress were settlement, shrinkage, and chemical attack. Erosion was the single most frequent factor causing distress; it was stated to have led to damage in 24 percent of the analyzed cases. Of the erosion cases classified, 54 percent were reported to have been caused by abrasion-erosion. The depth of wear-damaged scour holes in the surveyed hydraulic structures was reported to vary from a few inches to several feet, reaching 10 ft* in some locations.

Stilling basins and spillway aprons are highly susceptible to abrasion- erosion and should be periodically inspected and repaired to ensure their functionality, safety and the overall integrity of the hydraulic facility. Several stilling basins have rising end sills (3 to 20 ft) to form pools which help

* A table of factors for converting US Customary units of measurement to metric (SI) units is presented on page vii.

dissipate the energy of fast flowing water and prevent erosion of downstream river embankments. Eddy currents created by diversion flows, water discharge from neighboring power plants or turbulent flow within the stilling pool can result in adverse water conditions that can sweep riprap and other debris from a downstream riverbed back into the stilling basin. Whenever the exit channel of a stilling basis is not properly designed, rock and other waterborne debris can be trapped in the permanent stilling pool. Such debris can move over the concrete-lined base slab with the circulating water, thus continuously grinding the concrete and causing abrasion damage (McDonald et al. 1987).

1.1 Needs and Challenges of Underwater Repair

It is important to note that repairing damaged slabs or lining the bottom of hydraulic structures with wear-resistant materials can only reduce the rate of erosion and decrease the need for frequent repairs. Abrasion-erosion can only be prevented by eliminating adverse hydraulic conditions that lead to eddy current formations and debris entrapment and circulation. Such measures include the restriction of unbalanced and unsymmetrical water discharge to avoid the creation of eddy currents, the construction of low areas to entrap debris or low division walls to limit their circulation, and the periodical removal of such debris with controlled water flushing or by divers (McDonald 1980).

The majority of scour hole repairs have taken place after dewatering parts of the structure and carrying the restoration in the dry. Such practice enables the casting and consolidation of sound materials and facilities the supervision as well as the detection and correction of mistakes. Land-based repair techniques can range from conventionally formed and trowel-on concrete to polymer impregnation and crack sealing.

However, in several cases the dewatering of a hydraulic structure can interfere with the operation of the facility during the construction period and prove impractical and very costly. In fact, the cost of erecting a cofferdam and dewatering it may exceed the cost of the actual repair. Furthermore, dewatering parts of a structure may induce objectionable settlement resulting from the lowering of the water level. Therefore, many marine and hydraulic structures must be constructed and repaired while

submerged under water, while the underwater-cast concrete must achieve excellent adhesion to underlying damaged areas and develop durable surfaces.

Several modified and proprietary techniques have been used for casting concrete under water for the construction of cofferdam seals, bell-pier foundation, etc. Because of the large depths of such placements, the discharged concrete rarely comes into contact with water since the bottom of the casting device is kept embedded at least 3 ft within freshly-cast concrete. On the contrary, in repair operations the limited depth of some scour holes and the frequent movements of the placement device in water to repair neighboring areas may not permit the maintenance of a continuous end seal. Therefore, concrete may have to be dropped a short distance in water, hence, the propensity of concrete to segregate and intermix with water is increased. Furthermore, the relatively small volume of discharged concrete needed to repair a small scour hole can reduce the hydraulic head over that location that otherwise would tend to improve the spreadability and consolidation of the concrete. Unlike regular tremie concrete, repair concrete needs to secure sound and abrasion-resistant surfaces. Sophisticated materials and underwater placement procedures that can reduce the risk of water dilution and secure durable and flat repair surfaces need to be developed.

1.2 Factors Affecting the Quality of Underwater Concrete

1.2.1 Concrete Mix Portland cement concrete is a suitable material for the restoration of hydraulic structures since it is relatively inexpensive, easy to mix, and can cure in water. The proper selection of concrete-making materials and sound proportioning of the mix directly affect the quality of the concrete. Rarely will concretes suited for placement above water work well when cast under water. When placed in water, conventional concrete is prone to excessive intermixing with the surrounding water and can result in substantially lower strength and durability values than when cast above water Therefore, a new generation of concrete mixtures should be developed to resist water dilution, bond well to surrounding damaged materials and secure durable surfaces.

1.2.2 Placement Methods The selection of a placement technique depends on the size and depth of the scour hole to be repaired, available hardware and expertise, the size of the job and other economical factors. Whenever a properly designed concrete mixture is carelessly deposited in water, aggregates can segregate and cementitious materials can be eroded leaving behind soft materials. Therefore, a proper placement method must be selected to protect the fresh concrete from segregation and water dilution in order to provide adequate strength and reduce turbidity and pollution.

1.2.3 Water Conditions Important factors including water velocity, depth and temperature can pose restrictions on concrete properties such as washout resistance, cohesiveness and stiffening rate.

The above three factors are interrelated and should be collectively considered before selecting a repair strategy. For example, rheological properties needed to ensure dense and homogeneous concretes depend upon the selected placement technique and water flow conditions. Therefore, concrete case with a tremie pipe should be fluid enough to spread readily from the discharge location and result in flat surfaces. On the other hand, concrete cast under water in a skip, the compacted in place to repair shallow scour holes should be highly washout-resistant to resist intermixing with water, yet it should be plastic enough to reduce the needed compaction effort.

1.3 Research Objectives

Researchers and practicing professionals associated with underwater concrete construction and repair need to understand the significance of alternate concrete materials and proportions which affect the properties of fresh and hardened concrete. Unlike the construction of massive bell foundations or cofferdam seals, limited research and guidance have been established for selecting concrete materials and repair procedures that can ensure high quality repairs. Most conventional design and construction practices have been based upon prior experience and empirical tests with local materials or proprietary additives. In conventional tremie concrete, extensive use has been made of fly ash, but few applications have been carried out with high range water-reducing admixtures (HRWRAs), silica fume or anti-washout admixtures (AWAs).

The goal of this research is to develop concrete repair materials and compatible placement techniques that can ensure successful and cost effective repairs of scour holes of different sizes and depths under water. The results of this study should prove the reliability of such materials and placement methods and should encourage the repair of hydraulic facilities under water.

CHAPTER TWO

REVIEW OF REPAIR PROJECTS

2.0 Introduction

In reviewing remedy measures and subsequent performance of 921 wear- damaged structures, McDonald and Campbell (1985) reported that only eight structures were repaired while still submerged in water. The pump method was reported to have been employed satisfactorily for casting concrete in water on one repair job. Three projects made use of the tremie method, however, no performance data was available. Another method of repair used the grout-intruded aggregate technique, but the repair was reported to perform poorly.

Described below are selected materials and techniques used in the repair of five hydro-technical structures that were damaged by abrasion-erosion. The repair ranged from placing concrete under water using the tremie or preplaced aggregate methods, to dewatering parts of the structures and casting fibrous or silica fume concrete overlays. The performance of each of these techniques is also highlighted.

2.1 Webbers Falls Dam

The Webbers Falls lock and dam, located on the Arkansas River, was built in 1965 and became operational in 1970. The spillway stilling pool is approximately 100 ft long and 710 ft wide. The basin slab is approximately 4 ft in thickness and is anchored to the limestone foundation through No.11 bars grouted 10 ft into the bed-rock. Shrinkage and temperature reinforcements consist of No. 6 bars placed 12 in. apart in both directions near the top. The slab was designed for a f'_c of 3,000 psi. The maximum size of aggregate (MSA) was 3 in., except for the top 2 ft which used 1.5 in. aggregate. In 1973 and 1974 the spillway experienced a series of very large water discharges, up to 159,000ft^3/sec, over a 24 hr period which resulted in 30 ft/sec water velocities.

A routine underwater inspection in 1974 led to the discovery of large amounts of abrasion damage. The average depth of the damage was approximately 2 ft, although 4 ft deep scour holes were found near the end sill. Scour holes were cleaned of silt and debris using water jets and air lifts before filling them with tremie concrete. Barges were tied together to form a work platform over the repair area. Transit mixers loaded on the barges delivered concrete to buckets placed over a hopper that was attached to a tremie pipe. The end of the 10 in. diameter pipe was positioned by a diver over damaged areas, then raised up to release a greased polyethylene bag stuffed with burlap sacks which was used to reduce segregation at the start of the tremie placement. A total of 43 yd^3 of concrete was poured in 40 ft of water. The following is a listing of the mixture proportions in lb/yd^3 (pcy).

Cement, pcy	725	Sand, pcy	1,279
Water, pcy	341	1 in. MSA, pcy	1,567

The water was heated to offset the cold river temperature. An air- entraining admixture (AEA) was used to reduce segregation. The concrete slump ranged between 5 and 8 inches. Cores extracted from the repair slab after 60 days showed an approximate f'_c of 5,000 psi. The work was completed in 1975, and the basin was inspected under water a year later and was reported to be in satisfactory condition (McDonald 1980).

2.2 Chief Joseph Dam

Chief Joseph dam is located on the Columbia River in Washington State where annual discharges range from 350,000 to 500,000 ft^3/sec, and flood flow velocities could be greater than 100 ft/sec for approximately 6 months of each year. Its stilling basin is approximately 220 ft long and 920 ft wide and has a 5 ft thick slab that is attached to the foundation by grouted anchor bars.

In 1957, after 2 years of operation, extensive areas of eroded concrete were discovered in the slab and baffles. However, the erosion was relatively shallow except for two small scour holes between the baffles and the end sill which were approximately 5 ft in depth. By 1966, the wear damage progressed to a maximum depth of about 6 feet. Debris was removed, and 6,200 ft^2 of the concrete

surface was cleaned with wire brushes, water jets and an air-actuated dredger. Anchor bars were embedded and grounded, and horizontal steel bars were installed. The repair tool place in 26 ft of water that was flowing at approximately 0.5 ft/sec velocity.

Portions of the basin slabs were repaired using pre-placed aggregate concrete, where concrete buckets containing coarse aggregate were guided into position by divers and dumped under water. Screeds placed on pre-set edge forms were then used to level the aggregate before placing top form panels. Grout pipes were driven through the full depth of the aggregate. The deepest areas were grouted first until good sanded grout appeared through the vent pipes surrounding those areas, which were then plugged. A total 80 yd^3 of pre-placed aggregate was grouted.

Pumped concrete was also used to restore 439 yd^2 of damaged area. A 3 in. flexible hose was fitted with a metal tube at the last 2 ft to facilitate insertion in fresh concrete. A clamp was attached to the metal tube to help divers control the placement. A detailed inspection of the basin conducted in 1974 indicated that the repaired surfaces were in good condition, with only minor surface damage observed. Extended damage was noted only in one area where pumped concrete was too stiff and had a tendency to form a roll at the outside edges (McDonald 1980).

2.3 Old River Low Sill Structure

The Old River Control Structure, located on the west bank of the Mississippi River, was constructed in the 1950s and 60s. The width of the stilling pool ranges from 566 ft to 592 ft and the thickness of the reinforced slab is approximately 5 feet. Two rows of 10 ft high baffles spaced 12 ft apart extend across the basin.

An underwater inspection in August 1976 revealed abrasion damage between the downstream row of baffles and the end sill and also at the central part of the basin. The depth of the damage ranged from 6 in. to 2 ft, with isolated scour holes measuring 4 ft in depth. Retrieved debris varied from twisted reinforcing bars to large riprap.

In order to mitigate further damage and reduce construction time and cost, it was decided to use prefabricated steel modules which would span from the downstream row of baffles to the end sill. Thirty modules, 24 ft long with widths ranging from 3 to 22 ft, were fabricated from a 0.5 in. thick steel plate. Vertical diaphragms were welded to the horizontal plates to retain the grout and provide stiffening action. Partial closure of control gates was necessary to facilitate underwater operations. The modules were installed in a symmetrical way to avoid possible adverse hydraulic conditions. They were anchored to the underlying slab, then a fluid and fast-setting fibrous grout was pumped under them. The proportions of the grout mix were as follows:

Cement, pcy	1,034	AEA, fl oz	4
Sand, pcy	2,080	Water-reducing Admixture	
Water, pcy	466	(WRA), fl oz	11
1 in. Steel Fibers, pcy	100	Bentonite Gel, pcy	10

The grout was pumped approximately 100 ft down to a ready-mix truck located on a barge where it was remixed before pumping it under water in order to reduce segregation. The repair was completed in December 1976 at an estimated contract cost of $1,850,000. An underwater inspection carried out 8 months later showed that seven of the 30 modules had lost 20 to 100 percent of their surface area. Two years later, another inspection indicated that nine additional modules had suffered some damage, but that the fiber-reinforced grout surface was still in good condition (McDonald 1980).

2.4 Kinzua Dam

Kinzua dam is an earth-fill and concrete gravity dam in Pennsylvania. Its stilling basin is 178 ft long and 204 ft wide and has large baffles and an 11 ft high end sill. The basin slab has a minimum thickness of 5 ft and a 28 day f'_c of 3,000 psi. The slab was designed to relieve 50 percent of the uplift forces caused by hydraulic jump at maximum flood discharge. Closely-spaced No. 11 anchor bars were provided to resist any unrelieved uplift pressure. The basin was first used in March 1963, but normal operation began at the end of 1965.

An underwater inspection of the stilling pool was carried out in September 1969. It indicated the presence of several piles of debris and scour holes which were as deep as 3.5 feet. Non-symmetrical discharge from the right sluices, in conjunction with discharge from a nearby power plant, were believed to have caused a circulatory current which transported riprap and river gravel into the stilling basin (McDonald 1980).

A total of 50 yd^3 of debris was removed. The repair started in July 1973 by erecting cellular cofferdams in two stages to allow for water flow and avoid complete interference with the operations of the hydraulic facility. The dewatered cofferdam covered approximately 60 percent of the stilling pool area. The dry surface was cleaned by air jackhammers and wet sand blasting. Inverted U-shaped reinforcing bars were installed at 3 ft intervals and ground with a sand-cement mortar to anchor a fibrous concrete overlay. Deep scour holes were filled with conventional concrete then tapered with a high-modulus epoxy compound to bond the fibrous concrete overlay. The overlay mix proportions were as follows:

Cement, pcy	752	Water, pcy	300
Sand, pcy	1,573	WRA, pcy	1.42
5/8 in. MSA, pcy	1,092	AEA, pcy	0.56
1 in. Steel Fibers, pcy	200		

The 28 day f'_c of the fiber-reinforced concrete was 6,000 psi, and its 28 day flexural strength was 1,100 psi. The repair was completed in August 1974 with 1,400 yd^3 of concrete in place. The cost of constructing and dewatering the cofferdams was said to amount to 43 percent of the total repair cost (McDonald 1980).

An underwater inspection conducted one year after the repair resulted in the removal of 45 yd^3 of debris, another 60 yd^3 of debris was removed 5 months later. Surface damage was observed in the baffles and 4 in. to 12 in. deep scour holes were found in areas downstream from the baffles. A diving inspection in June 1977 indicated that the fibrous concrete slab had been eroded to a maximum depth

of 3 feet. Another inspection in 1978 revealed additional damage where the first two rows of slabs immediately downstream of the spillway experienced severe damage. One location was reported to have a scour hole with a 4 ft depth (McDonald 1980).

The stilling basin was dewatered again in June 1983 for a new repair. The fibrous overlay was removed, and the surface of the old concrete was cleaned by wet sand blasting and high pressure water jetting. A high strength concrete overlay was placed and anchored in the base slab using No. 8 dowel bars. The concrete had a water-to-cementitious material ratio (W/CM) of 0.28, a 9.75 in. slump and a 3.2 percent air content (Krysa 1984). The in-place 28 day f'_c was 11,990 psi. Mix proportions were as follows:

Cement, pcy	650	3/4 in. MSA, pcy	1,637
Silica Fume Slurry, pcy	263	Sand, pcy	1,388
Silica Fume in Slurry, pcy	(118)	Additives in Slurry, pcy	(11)
Water in Slurry, pcy	(134)	Added Water, pcy	85

A total of 2,014 yd^3 of the silica fume concrete was used to cast 54 slabs measuring 30 × 20 × 1 ft each. The concrete was consolidated and then tapered with vibrating screeds. The slabs experienced severe cracking which was attributed to thermal gradients within the highly restrained slabs. The repair was completed at a cost of $1,355,200.

Diver inspections in August of 1984 revealed that the slab was sound, except for approximately 0.5 in. deterioration along existing cracks and joints which later were reported to grow latter and wider. Subsequent diver inspection revealed that the basin was in good condition, except for some damage along the toe of the structure. In general, the soundness of the slab was thought to be accounted to both the highly wear-resistant silica fume concrete and the construction of debris trap.

2.5 Tarbela Dam

Tarbela Dam is one the world's largest dams and is a vital structure for the irrigation and water control of the Indus and two of its tributaries in Pakistan. The dam has four irrigation tunnels and

stilling basins with 10 ft thick base slabs. The two right bank tunnels (three and four) have identical outlet control structures with a middle wall separating their stilling basins. They were first used in the summer of 1974.

A sudden collapse of one of these tunnels led to an emergency discharge of water from the reservoir. The non-symmetrical discharge of water rushing at a 160 ft/sec velocity caused eddy currents to form and transport rock debris from downstream into the stilling pool resulting in severe abrasion-erosion. In Spring 1976, sounding surveys of tunnels three and four isolated 10 ft deep scour holes. A diver inspection in 135 ft of water revealed massive erosion at the bottom and side walls of stilling basin number three. The erosion undercut the dividing wall between the two basins and seriously endangered the safety of the dam.

In order to repair the stilling basin, massive eroded areas were filled under water with tremie concrete to stabilize the structure. The stilling basin wall was then underpinned, and the basin was dewatered to cast a reinforced concrete slab in the dry (Anon 1976). Prior to underwater operations, loose sediments in the scour holes were removed using water jets and airlifts. A floating platform made of two rows of pontoons and a simple portal structure was used to support three overhead winches which raised and lowered three 12 in. diameter tremie pipes. Three 90 yd^3/hr pumps were used to deliver concrete to the pipes.

Two mixes were selected, one with 1.5 in. MSA, and another with 3/4 in. MSA; the latter was used for congested areas. Mix proportions and properties were as follows:

MSA, in.	1.5	3/4
Cement, pcy	548	624
W/CM	0.57	0.58
1.5 in. MSA, pcy	1,087	--
0.75 in. MSA, pcy	821	1,670
Crushed Sand, pcy	1,104	1,283

Natural Sand, pcy	278	321
28 day f'_c, psi	3,780	4,210

A WRA and an AEA were incorporated to enhance the fluidity of the concrete. The average slump and air content of the two concretes were 7.5 in. and 6 percent, respectively. Tremie concrete was placed in 12 ft lifts (Anon 1976).

Over 90,000 yd^3 of tremie concrete were poured under water. The placement rate ranged from 52 to 160 yd^3/hr, depending on the ambient temperature. At the completion of the underpinning, the basin was dewatered to cast a 10 ft thick reinforced concrete slab which was anchored with dowels to the underlying tremie-cast concrete. After 1 year of operation, the base slab was reported to have experienced severe abrasion damage, and the stilling basin was dewatered to cast a 20 in. thick fibrous concrete slab A total of 8,000 yd^3 of fiber-reinforced concrete was needed. The basin was in operation for 9 months where flow velocities ranged from 83 to 155 ft/second. The overlay was inspected in the dry and later under water with television (TV) cameras and seemed to be sound, except for isolated areas. The repaired joints did not seem to experience serious spalling (Chao 1980).

CHAPTER THREE

REVIEW OF UNDERWATER PLACEMENT METHODS

3.0 Introduction

In general, two types of fresh concretes can be used for repairing scour holes underwater: fresh concrete can be placed by tremie pipes, pumps, buckets or other modified methods; or cement grouts can be pumped through pre-placed coarse aggregate. The choice of a placement technique is dictated by several factors, such as the volume and thickness of the repair slab, the presence of reinforcing steel, water velocity, desired inplace properties as well as the availability of specialty equipment and expertise. Several methods that can be employed for underwater repairs are described below. In general, a superior placement method should fulfill the following characteristics:

A. Ability to deliver concrete with minimal segregation and water erosion.

B. Freedom of choice of the discharge location and movement under water.

C. Freedom of choice of concrete composition.

D. Controlled rate of discharge to monitor lift thickness and surface tolerance.

E. High placement capacity.

3.1 Tremie Concrete

Tremie concrete is a gravity feeding technique whereby concrete is fed into a hopper attached to the top of a vertically-suspended pipe. The diameter of the tremie pipe diameter varies between 6 and 12 inches. The pipe is normally assembled in sections that are tightly connected. Prior to submerging the pipe in water, its bottom should be capped to prevent water from entering the pipe and eroding the fresh concrete. The end of the pipe is then lowered to the desired repair location and set on the bottom. A rich and highly cohesive mortar is usually placed in the pipe to lubricate it and provide an initial mound of cohesive material through which subsequent concrete is initially discharged. Regular

tremie concrete is then poured into the tremie pipe, and the pipe is raised approximately 6 in. in order to break the seal and allow the concrete to flow out.

Tremie concrete usually contains approximately 650 lb/yd^3 of cement with approximately 25 percent fly ash replacement. The average W/CM and slump values are usually 0.45 and 8 in., respectively (Gerwick et al. 1981). Well rounded natural gravel with nominal sizes of 3/4 in. are often used. The sand content is usually 42 to 50 percent of the aggregate weight. An AEA, a retarder and a WRA are frequently incorporated to enhance the rheological properties of the concrete.

Tremie pipes are normally spaced 15 to 20 ft apart, although much wider spacings may be achieved with retarded and highly mobile concrete mixtures (ACI Committee 304 1972). Normally, the bottom of the tremie pipe is embedded 3 to 5 ft within fresh concrete to protect the discharged concrete from segregation and water erosion. Conventional tremie operations can be used for repairing deep scour holes where the end of the tremie can be immersed within fresh concrete. However, the limited depth of shallow scour holes may inhibit the maintenance of a continuous end seal. Therefore, concrete should incorporate an AWA to minimize segregation and water dilution.

In 1987, the tremie method was used to fill 16 bell foundations located 780 ft under water with high strength concrete in order to stabilize an offshore drilling platform in Australia (Bemer at al. 1989). The concrete employed 265 lb/yd^3 of cement, 752 lb/yd^3 of blast furnace slag and 32 lb/yd^3 of silica fume. Sea water was used for the mixing water, and the W/CM was fixed to 0.33. The concrete used a high dose of a WRA (Sika Plastiment) to achieve a slump of 8 inches. The f'_c at 28 days was 8,700 psi.

Pre-cooled concrete was cast in 6 in. diameter drill casing lines located inside the legs of the platform which was inclined 7° from vertical. A pig was placed ahead of the tremie concrete to reduce the intermixing with water. The concrete proceeded down the pipe by gravity and spread around congested steel cages located in the belled cavities. The project proved that well proportioned high strength concrete can be reliably placed at great depths using proper tremie operations.

3.2 Hydro-Valve Method

This gravity feeding method was developed in 1968 in the Netherlands. It comprises of placing discrete slugs of fresh concrete through a flexible hose made of PVC-coated nylon sheets that are sealed together. A heavy steel shield is provided at the lower 3 ft of the hose to stabilize the Hydro-valve. The tubing is surrounded and supported by a set of connected rings placed at regular intervals.

The flexible walls of the hose are forced together when the device is submerged in water. Once the bottom of the valve is at the desired location, concrete is charged into the pipe. When enough mass is accumulated inside the valve, the concrete forces the walls apart and progresses slowly downward. Regardless of the fluidity of the concrete, any desired quantity of concrete can be delivered without much segregation.

For repairing large damaged areas, the outlet end of the valve can be kept at a constant position where concrete is placed until it spreads out. Then the valve can be moved horizontally over the edge of previously-poured concrete. Several lifts can be poured to build up the required thickness in successive layers (Figure 1, Appendix A). The density of concrete placed under water with a Hydro-valve can be as high as 98 percent of that placed on land (International Foundation Company). A relatively smooth surface may be secured by installing a probe at the lower end of the shield to sense the surface of underlying material. It is claimed that the thickness of the underwater-placed concrete can be controlled to achieve a surface tolerance of ± 4 in. (Schoewert et al. 1972).

Figure 2 (Appendix A) shows a schematic diagram of a modified Hydro-valve with a force-feeding mechanism. The tube contains an electrically-driven screw-feed auger which rotates to drive the concrete from the top hopper into the valve. This system was reported to facilitate the placement of stiff concrete (Hillen 1969).

3.3 Kajima's Double Tube Tremie Method (KDT)

This technique is similar to the Hydro-valve method, except it employs a perforated steel pipe that surrounds an inner flexible tube to enable the outlet end to be inserted within fresh concrete. Figure 3

(Appendix A) illustrates schematically the various steps involved in placing such concrete in water (Nakahara et al. 1976).

In an attempt to evaluate the effectiveness of this method, four 10 x 3 x 3 ft beams were cast in 30 ft of water using four different concretes that had approximately 7 5 in. slump values. One third of the concrete was first discharged at one end of the beam, then the pipe was retrieved and moved to the other side to deposit another third. The final portion was placed back at the first discharge location. The beams were cured under water then recovered for coring. Mix proportions and results were reported as follows:

Beam	A	B	C	D
Cement, pcy	623	623	539	455
MSA, in.	1	1	1.5	1
W/CM	0.48	0.46	0.54	0.64
f'_c Cast in Water, psi	5,160	4,295	3,340	2,800
f'_c (Under Water/Air)	1.09	0.92	0.98	0.99

According to the above results, the placement of sound concrete with the KDT tremie method seems to secure in-place concrete quality comparable to that cast above water, even for lean mixes (Nakahara et al. 1976).

3.4 Pumped Concrete

The pump method for casting concrete under water offers the following advantages:

A. Concrete is transferred directly from the mixer to the point of discharge without the need of hopper or hoisting rigs.

B. The bottom of the pump line may be buried deep into plastic concrete to enhance the bottom seal and reduce the frequency of pipe movements.

C. The rate of placement can be controlled by adjusting the pumping pressure.

However, it is also important to note that pumping concrete under water has the following drawbacks:

A. Concrete discharged under water by pumping may proceed out of the pump line at higher velocities than those resulting from gravity feeding, thus increasing the risk of water erosion. Pumped concrete is normally placed in surges which can disturb freshly-cast concrete.

B. Concrete pumped downward can fall faster than the driving action provided by pumping. Therefore, air pockets or a vacuum can be created within the pump line leading to segregation.

C. High pumping pressures can force part of the mix water into coarse aggregate, thus causing reduction in fluidity.

If the pump method is chosen, it is desirable to mount the pump line to a boom mast. This can facilitate the relocation of the outlet end of the pump line to repair neighboring scour holes and can also reduce the vibration and disturbance to freshly-cast concrete. A typical pump line may consist of a 3 in. hose which is fitted with a metal tube at the final 2 ft in order to permit its insertion into plastic concrete. At the commencement of pumping a suitable plug, such as a polystyrene block, should be inserted at the end of the line adjacent to the pump. The plug travels ahead of the concrete, thus reducing segregation and intermixing of the pumped concrete with water at the leading edge. Whenever possible, the pipe end should be embedded 3 to 5 ft within fresh concrete.

3.5 Sabema Foot Valve

A patented Abetong-Sabema pneumatic valve is fixed to the bottom of an articulated distributor boom-pipe. A schematic view of this valve is shown in Figure 4 (Appendix A). By remote control, compressed air is pumped into the annulus between the sleeve and the tube forcing the internal rubber sleeves together, thus preventing concrete from passing through. The valve is shut off before lowering the pump line into water. Once the end of the line is above the desired repair area, the casting pipe is filled with concrete and the compressed air is released, hence allowing the concrete to flow out.

The valve should be closed before relocation to avoid concrete from falling through water and water from entering the pipe and eroding the fresh concrete inside. As a result, the turbidity and contamination of the water can be reduced.

The Sabema valve was employed to cast 15 bridge seals at approximately 88 ft of water for the Faro Bridges in Denmark. Each plug was 12 ft deep and required approximately 880 yd^3 of concrete. The pump line consisted of a 4 in. casting tube surrounded by a water-tight mantle made by a 13 in. steel pipe to provide some buoyancy to the casting pipe. The pipe end was embedded 3 ft in fresh concrete. The mix proportions are listed below.

Cement, pcy	556	Fly Ash, pcy	168
Sea Sand, pcy	977	WRA, pcy	22.2
Crushed Granite, pcy	598	HRWRA, pcy	8.3
Sea Gravel, pcy	1,264	AEA, pcy	1.7
Water, pcy	253	Retarder, pcy	7.2

The concrete mix had a 23 in. flow value, a 4 percent air content, and a final setting timer of 30 hrs (Remmer et al. 1982). Published information describing the actual performance of the Sabema method on that project was not available. However, it seems that the underwater casting of the concrete was often interrupted because of aggregate plugging the foot valve. The final cost of casting the 15 bridge seals was believed to be approximately four times more expensive than what it would have cost had a conventional tremie pipe been employed (private communication, Gerwick 1989).

3.6 Shimizu Foot Valve (NUCS Device)

A proprietary pneumatic foot valve, known as a NUCS device, was introduced by the Shimizu Corporation. This device is similar to the Sabema pneumatic valve. The valve is attached to the bottom of a pump line or tremie pipe. A schematic diagram of the apparatus is shown in Figure 5 (Appendix A). A set of detectors are attached to the bottom of the pipe at different elevations to sense temperature differences between water and the rising concrete and convey various signals to an

operator above water. Shimizu suggested that predetermined depth of concrete can be delivered, and uniformly thick lifts can be obtained (Shimizu Technical Report 36). A simplified penetration resistance tester is attached to the bottom of the valve to verify that the underlying material has not hardened before casting another concrete lift.

The NUCS device was used to cast 840 yd^3 of concrete in 6 to 20 ft of water to construct a cofferdam seal for a bridge foundation in Japan. The valve was attached to the bottom of a pump line and was moved to cast concrete in successive layers at several locations over 2,000 ft^2. Discharge locations were spaced 10 ft apart. The placement proceeded at an average rate of 45 yd^3/hour. The cement content was 625 lb/yd^3, and the W/CM was 0.51. An AEA was used to obtain an air volume of 4.5 percent. The concrete had an average slump of 7 in. and resulted in an approximately surface profile of 1:11. The average in-place f'_c was reported to be 3,400 psi (Shimizu 1978).

Shimizu also employed the NUCS device to cast its JOILUC (JOIntLess Underwater Concrete) material under water. This concrete contains a cellulose-ether based admixture and melamine and lignin condensate additives. The placability of this concrete was checked by pumping 10 yd^3 of concrete in a 60 × 2.5 ft basin filled with 3.5 ft of water. The concrete was made with a W/CM of 0.44 and contained 725 lb/yd^3 of portland blast furnace slag cement. All concrete was discharged near one end of the placement box. The surface profile of the hardened concrete was claimed to be flat, and the 28 day average in-place f'_c was 4,300 psi (Kawai et al. 1986).

A 15 × 1.8 ft reinforced beam was cast in water using the above concrete and valve. Steel bars were spaced 6 in. apart in three dimensions. The initial surface gradient was 1:5 and was reported to proceed slowly to final slope of 1:32. The concrete was said to have flowed well between the steel bars and developed adequate strength (Kawai et al. 1986).

3.7 Kumagai Gumi Foot Valve

The Kumagai Gumi Corporation also introduced its KTS-1 valve, shown in Figure 6 (Appendix A). It comprises of a hydraulically operated crushing valve which is fitted near the bottom of a tremie pipe.

A rigid plate is forced across the pipe perpendicular to the flow direction to restrict its opening and control the concrete discharge. Three specially designed floats are provided outside the pipe at predetermined elevations from the bottom of the pipe to detect the rising concrete surface and ensure embedment in plastic concrete.

The valve was employed to cast a 13 ft deep and 17 ft diameter base slab for a bridge caisson in Japan. K-Crete, a proprietary concrete containing an AWA, was used. Its mix proportions were as follows:

Cement, pcy	541	W/CM	0.50
Sand, pcy	982	1.5 in. MSA, pcy	1,201

Both a HRWRA and an AWA were employed. The average slump was 10 in., and the average 28 day f'_c was approximately 4,800 psi. The crushing valve was attached to the bottom of a 6 in. tremie tube, and concrete was transferred to the pipe by pump. The placement was carried out in 80 ft of water. The concrete was said to flow well and result in surface gradients ranging between 1:6 and 1:180. The average reported in-place 28 f'_c was 4,000 psi (Yamaguchi 1986).

3.8 Bucket and Skip Methods

Covered bottom-dumping buckets or skips, equipped with air-operated gates, are attractive alternatives for delivering small volumes of highly washout-resistant concrete under water. Such concrete can be useful for patching shallow eroded areas or casting wear-resistant overlays (Chapter Ten). Tilting pallets can also be used to deliver such concrete under water. The concrete can be spread flat and consolidated using rollers or vibratory pressure plates (Gerwick 1985).

3.9 Grout-Intruded Aggregate

The grout-intruded aggregate method is more complicated and costly than conventional tremie or pumped techniques. Special care should be taken since this method has led to several failures. Bleed water and displaced water can get trapped under the coarse aggregate resulting in weak bonding between the cement paste and aggregate, thus leading to subsequent failure. Similarly, algae growth can

cover the aggregate surface before grouting and prevent sound bond developments. Other failures were accounted to the presence of large ungrouted pockets resulting from the plugging of interstices by sand and rock chips.

The use of grout-intruded aggregate technique is currently limited to deep pier construction in Japan. However, this methods may be effective for repairing large and deep damaged areas where a high uninterrupted casting is desired. If this method were to be used, grout tubes should be placed inside scour holes, and bagged concrete can also be used at the hole boundaries to retain the aggregate and grout. Tilting pallets or bottom-dumping skips can be utilized to deliver the rock under water. Clean and hard coarse aggregate must be employed. The nominal size of the aggregate should be large to reduce the void content. Natural sand with fineness modulus between 1.65 and 2.10 is recommended (Davis 1960).

A venting cover should be used to retain the grout on top and enable it to fully encompass the aggregate there and allow air and water to escape. Insert pipes are normally 0.75 to 1.5 in. in diameter and are usually spaced 4 to 12 ft apart. Their lower ends should be positioned no more than 6 in. from the bottom at the beginning of the grouting, and should be buried at least 12 in. in fresh concrete, whenever possible.

A high quality grout mix may consist of nine parts of cement, one part of pozzolan, six parts of sand and a W/CM of 0.45 to 0.50 (Davis 1960). It is recommended to incorporate an AWA and a HRWRA to minimize bleeding without affecting the workability, groutability and stability of the grout. Colloidal grout mixers can be employed to ensure uniform dispersion of cement particles. It is recommended to employ a positive displacement pump (such as a piston or a progressive cavity type pump) to pump the grout into the insert pipes (ACI Committee 304, 1969).

CHAPTER FOUR

RELEVANT CONCRETE PROPERTIES

4.0 Introduction

The characteristics of fresh and hardened concrete directly affect is placability and durability, and hence the quality of the repair. Unfortunately, several of the important properties that need to be achieved are in contradiction to one another. For example, it is difficult to obtain a highly flowable concrete without endangering its resistance to segregation and water erosion or strength. However, by properly selecting concrete-making materials, sound mix proportions and use of special additives, promising repair concretes can be tailored to achieve good balance between the different desired rheological and mechanical properties.

4.1 Rheological Properties

4.1.1 Workability and Placability The workability of concrete describes the relative ease of mixing, transporting, casting, consolidating and finishing fresh concrete without segregation. Powers (1932) suggested that the consistency of plastic concrete depends on the relative volume and consistency of the paste, as well as the aggregate type and gradation. Tattersal (1976) added that the workability of concrete is affected by the time elapsed since mixing; the properties of cement; the presence of admixtures; the mix proportions; and the aggregate shape, size distribution, porosity and surface texture.

The required consistency depends on the adopted placement method. Table 1 (Appendix B) reproduces concrete consistency values that are recommended by the Kajima Corporation (Kajima 1985) to facilitate the casting of concrete when various placement methods are used. Tremie concrete should be fluid enough to spread away from the discharge pipe, self-compact and form relatively flat surfaces, yet it should be cohesive enough to resist segregation and water erosion. High mobility should be maintained even when the cement content is increased and silica fume is employed to enhance the

durability of the hardened material. WRAs should be incorporated to reduce the water demand, especially when an AWA is used. However, a high WRA dose may cause excessive delays in setting time. Therefore, a HRWRA can be used provided it does not lead to accelerated fluidity loss, even at elevated temperatures.

Special attention should be given to the workability of pumped concrete. For example, if the concrete is very fluid and not cohesive enough, the pumping pressure may force some of the excess water out of the cement paste and lead to segregation. On the other hand, if the concrete is dry and harsh, the placement rate may be reduced or excessive pumping pressures may be required. This can lead to blockages of the line which may cause unacceptable construction delays. The size, shape and gradation of aggregates, especially pertaining to fine aggregate, greatly influence the pumpability of the concrete and should be carefully selected.

Sticky concrete that is cast under water in closed buckets, then spread and compacted in place must be highly resistant to water erosion, yet it should be plastic enough to reduce the required compaction effort. A rich concrete containing a high concentration of AWA and silica fume should be used for this application. The setting time should be retarded to allow enough time for underwater operations.

4.1.2 Stability and Homogeneity The stability of fresh concrete is characterized by bleeding and segregation, which in turn are affected by the mix proportions, aggregate shape and gradation. Whenever the cohesiveness of the cement paste is low, individual aggregate particles may not be retained in homogeneous dispersion. Therefore, heavy particles an settle down causing a number of capillaries to form allowing water to escape to the top. Some of this water may get trapped under large aggregate particles or reinforcing bars. The rest of the rising water migrates upward, transporting with it fine and soft particles which are then deposited on the top surface (laitance). Excessive bleeding can be detrimental to the abrasion resistance of the concrete and its bonding to subsequent concrete lifts and reinforcing steel.

The cohesiveness of fresh concrete can be improved by reducing the water content or by using a WRA, HRWRA or AEA. Similarly, increasing the cement content, adding pozzolans, or using sand with an adequate content of fines can enhance the stability of the concrete. A large increase in aggregate content or decrease in W/CM can lead to a harsh mix of low cohesiveness which can break up and segregate. Conversely, large decrease in the aggregate content or increase in added water or HRWRA can reduce the cohesiveness and lead to wet segregation.

4.1.3 Washout Resistance Whenever concrete is cast through water, the differential velocity at the interface between the fresh concrete and surrounding water can erode cementitious materials and other fines from the concrete. Such erosion can dramatically impair the strength and abrasion resistance of the concrete. The magnitude of the differential velocity depends on the method of placement and water movements. The susceptibility of concrete to water erosion depends on the ability of the fresh mix to retain its water and fines. AWAs can be used to enhance the water retentivity of the concrete. The washout resistance can also be improved by using a rich and cohesive concrete that incorporates a high concentration of silica fume.

4.1.4 Other Properties It is essential that fresh concrete maintain its high fluidity while being transported, handled and placed under water. Therefore, the consistency of concrete containing a HRWRA should be monitored over time. Any type of HRWRA that results in sharp fluidity reduction should be avoided. Excessive delays in setting should be avoided to reduce water erosion caused by moving water over freshly-placed concrete. Excessive generation of heat must be prevented to reduce sharp thermal gradients across relatively thin and highly restrained repair slabs. Several steps could be taken to reduce heat rise, such as reducing the cement content, using pozzolans and lowering the initial concrete temperature.

4.2 Mechanical Properties

4.2.1 Abrasion Resistance Providing that fresh concrete is properly placed under water, its ability to resist abrasion-erosion is the single most desirable characteristic. Measures that improve the strength

of the hardened cement paste and the bond strength between the paste and the aggregate usually enhance the wear resistance of the concrete.

The hardness of the coarse aggregate, which comprises the greatest volume in concrete, has a direct bearing on abrasion resistance. In an effort to evaluate the suitability of materials for repairing stilling basins, Holland (1983) compared the abrasion weight loss of several mixtures and surface coatings using the "Underwater Method" of measuring abrasion-erosion resistance (test described in section 5.2.1). It was found that greater resistance can be provided when hard aggregate are used. For example, a concrete containing hard chert aggregate with a f'_c of 5,700 psi which was made with softer limestone aggregate. In addition to strength and aggregate hardness, Liu (1980) suggested that the mode of aggregate failure can affect the abrasion resistance of the concrete. For example, chert tends to chip, and hence it can develop friction and delay abrasion damage, whereas limestone may crush, thus it can accelerate wear damage.

In examining two concretes having comparable strengths and using aggregates from the same source, the concrete with the larger nominal aggregate size can be expected to provide greater wear resistance than the one using the smaller aggregate (Holland et al. 1987). This is because the former contains a higher volume of coarse aggregate which leads to lower wear damage. However, whenever high fluidity and cohesiveness are required, small aggregate size (less than 3/4 in.) is recommended to enhance fluidity, reduce segregation and improve the interface between aggregate and cement paste.

In addition to aggregate properties and contents, other equally important factors affecting abrasion resistance are the hardness of the cement matrix, bonding between the hydrated cement paste and the aggregate, as well as the extent of compaction and curing. The quality of the interface between the aggregate and the cement paste depends mainly on the aggregates surface characteristics, its chemical interaction and adhesion to cement paste, thermal and mechanical compatibilities between the aggregate and the cement paste, the quality of the paste itself, and the bleeding of the fresh concrete.

The hardness of the cement paste and its bonding to aggregate can be enhanced by incorporating silica fume. Holland (1983) reported that silica fume replacement of 15 percent of cement weight can provide 30 percent greater abrasion resistance than concrete without silica fume, which had an even lower W/CM. The reduction of W/CM or an increase in cement content can also improve the wear resistance of the cement matrix and its interface with aggregate. In general, concrete made with the hardest available aggregate should be employed. Otherwise, local aggregate can be used providing that the cement matrix is toughened with silica fume and the W/CM is kept low.

4.2.2 Bond Strength Wear-damaged surfaces are usually smooth and should be roughened to develop good mechanical interlock with repair concrete. Loose materials should be removed and damaged surfaces should be cleaned. Underwater-placed concrete must bond well to repair surfaces, reinforcing steel, and dowel bars in order to ensure successful and durable repairs. This is especially important since it is not practical to use bonding agents (such as epoxies) before casting concrete underwater.

Several measures that enhance the quality of the cement paste and reduce bleeding and water erosion and can improve adhesion to repaired surfaces and reinforcing steel. For example, the addition of an AWA reduces water erosion and bleeding. Similarly, the use of silica fume can enhance the interface between the steel and hydrated cement paste, thus providing greater adhesion, even when the strength is kept constant (Monteiro 1985).

4.2.3 Cavitation Resistance In general, cavitation occurs when the water velocity exceeds 40 ft/second. Spillways, sluiceways and outlet surfaces are highly susceptible to cavitation-erosion. On the other hand, stilling basin slabs are submerged under water and are subjected primarily to abrasion-erosion.

Surface irregularities can cause a localized increase in flowing water velocity and a sharp reduction in pressure which can cause the intrusion of small bubble-like cavities of water vapor and air. As these bubbles flow downstream into higher pressure fields, they collapse creating extremely high pressures in a very short period of time, leading to very large stresses to nearby concrete. Repeated

stresses can indent the concrete surface leaving behind growing irregularities that can alter the water flow and aggravate additional erosion. Furthermore, high water velocities can impact eroded areas and lead to spalling and further damage. Similarly, the repeated collapse of air bubbles can induce periodic vibration that can lead to structural deterioration and de-bonding between the concrete and reinforcing steel (ACI 210, 1987).

Borge and Paxton (1978) evaluated the cavitation resistance of steel fiber-reinforced, polymer and conventional concretes by subjecting 120 × 33 × 3 in. slabs to water flowing at a 120 ft/sec velocity. The test was terminated when the maximum eroded depth reached 3 inches. The fibrous and polymer impregnated concretes showed equally high cavitation resistance levels. When fiber-reinforced concrete was polymerized, its cavitation resistance was considerably enhanced. Fibrous concrete containing high concentrations of silica fume and AWA may be cast and consolidated under water to yield cavitation-resistant slabs. Such concrete is hard to mix and spread under water, however, it may be more economical and easier to cure and bond to damaged surfaces than polymer or epoxy resin concretes.

CHAPTER FIVE

TEST METHODS FOR EVALUATING REPAIR CONCRETES

5.0 Introduction

Simple laboratory tests should be employed to evaluate the effectiveness of various materials and additives to enhance the desired rheological and mechanical properties presented in the previous chapter. Such tests can also be used to assess the performance of different concretes and qualify promising ones for actual repairs. A thorough testing program undertaken to finalize repair concretes can ensure sound repairs and help reduce the cost and risk associated with actual field placements. A number of simple tests should also be employed at the job site to monitor the quality of the delivered concrete and assure the beneficial effects of the various additives.

A number of standard and non-standard tests that were employed in this study to evaluate and optimize repair concretes are described here. Several of these tests are qualitative in nature and should be used to compare materials tested at similar conditions.

5.1 Testing for Rheological Properties

5.1.1 Slump Test Fluid concrete cast in water can be subjected to dynamic forces, such as those encountered during pumping or those caused by the concrete head in deep tremie placements. The slump test (ASTM-C 143, CRD-C 5) is a quasi-static test that does not recognize the mobility of the concrete under vibration. Furthermore, it does not adequately reflect the mobility of well plasticized mixtures. Even when small aggregates are employed, slump values greater than 10 in. are not very meaningful since concrete flows down quickly upon the removal of the slump cone. However, such values are useful for concretes containing AWAs since the viscous concrete proceeds slowly after the cone removal. Slump measurements of concretes containing AWAs should be delayed for one minute until the plastic flow of the material stops.

5.1.2 Flow Test The assessment of high mobility values can be provided by measuring the outer diameter of the concrete at the conclusion of a slump test. Such value reflects the ease of spreading and leveling when concrete is not subjected to vibration. The deformation of fresh concrete under external dynamic forces can be assessed using a flow table device (DIN 1048 - 1978, BS 18881 - 1984).

The table consists of a wooden upper board covered with a steel plate. The board is hinged at one end to a base wooden board. The vertical movement of the upper board on the opposite end of the hinge is restricted to 1.57 in. (Figure 7, Appendix B). A cone measuring 8 in. in height is used. Its upper and lower internal diameters are 5.4 and 8 in., respectively. The cone is placed at the center of the steel plate and filled with two equal layers of concrete that are compacted 10 times using a 1.5 × 1.25 in. wooden tamper. After removing the cone, the upper plate is lifted 1.57 in. and allowed to drop 15 times within 15 seconds. The arithmetic mean of four base diameter measurement is reported. These measurements should be delayed for one minute when AWAs are incorporated.

5.1.3 Underwater Leveling The ability of concrete to spread and self-level is of great concern for fluid repair mixtures. This characteristic should be evaluated since the leveling of concrete is a function of its density which is different for concrete submerged under water than that cast on land (buoyancy effect).

A non-standard test was developed by the author to monitor the ability of fresh concrete to spread and level under water. The test consists of charging three 12 in. layers of concrete into a 6 in. diameter pipe. Each 0.2 ft^3 lift is compacted 25 times with a wooden pole measuring 0.75 in. in diameter. The bottom of the pipe is placed over a placement box filled with 12 in. of water, as shown in Figure 8 (Appendix B). A quick-release lever is used to open a trap gate and permit the concrete to fall into the box. The water is then siphoned out, and the surface elevation of the concrete is mapped at 6 in. intervals to evaluate surface profiles.

5.1.4 Segregation A segregation susceptibility test, originally introduced by Hughes (1961) and subsequently revised by Ritchie (1966), was modified by the author to evaluate the separation of coarse aggregate from fresh concrete when cast under water. The test describes the scattering of concrete after having been dropped over a cone from two hoppers, once in air and another time through water.

A schematic of the apparatus is shown in Figure 9 (Appendix B). The upper hopper is filled loosely with concrete, then a trap door is opened allowing the concrete to drop into the lower hopper. The concrete is then allowed to fall from over a smooth steel cone, in air or through water, and scatter onto two cocentric wooden disks. For the underwater test, the basin is dewatered to examine the concrete. Pictures of dry-cast and underwater-cast concretes are shown in Figure 10 (Appendix B). The material over each disk is collected and weighed, then wet-screened with a No. 4 sieve. The retained coarse aggregates are oven-dried and weighed. The test yields the following parameters:

Dry Test	Concrete Spread, dry (CS_{dry}) = $(C_o/C)\ 100$
	Aggregate Spread, dry (AS_{dry}) = $(A_o/A)\ 100$
	Separation Index, dry (SI_{dry}) = $AS_{dry} - CS_{dry}$
Underwater Test	Concrete Spread, under water (CS_{uw}) = $(C_o/C)\ 100$
	Aggregate Spread, under water (AS_{uw}) = $(A_o/A)\ 100$
	Separation Index, under water (SI_{uw}) = $AS_{uw} - CS_{uw}$
Difference	Separation Resistance (SR) = $(SI_{uw} - SI_{dry})\ 100/SI_{dry}$
where	C_o = Weight of concrete on outer disk
	C_i = Weight of concrete on inner disk
	A_o = Oven dry weight of aggregate on outer disk
	A_i = Oven dry weight of aggregate on inner disk
	$C = C_o = C_i$ and $A = A_o + A_i$

Both CS and AS values describe the percentage of concrete and coarse aggregate, respectively, deposited on the outer disk. The spread between these two values (SI) measures the degree of separation

of aggregate from concrete and hence provides an indication of the homogeneity of the concrete. Stiff concrete with limited flowability may result in small CS and AS values. On the other hand, fluid mixtures can have a considerable amount of concrete on the outer plate since the inner one is relatively small compared to the drop distance. The concrete deposited on the outer disk does not describe its tendency to segregate. Instead, the difference between aggregate and concrete concentrations there (SI) reflects the susceptibility of concrete to segregate. A small SI indicates the ability of the unconsolidated concrete to stay together.

Concrete placed under water can be expected to segregate more than that cast above water due to the reduction of cohesiveness caused by water erosion. The difference between the underwater and dry SI values (SR) describes the resistance of additional aggregate to separate from concrete due to casting through water. The lower the SI_{dry}, SI_{uw} and SR values, the less the susceptibility of concrete to segregate.

5.1.5 Resistance to Water Erosion A washout test was developed (Inter-Beton 1982) to evaluate the ability of fresh concrete to resist intermixing with water. The test consists of determining the weight reduction of a fresh concrete sample after three drops through a determined column of water. A fresh concrete sample measuring 4.40 ± 0.44 lbs is placed in a perforated basket measuring 5.1 in. in diameter and 4.7 in. in height. The basket is made of 1/16 in. thick sheet-metal with 1/8 in. staggered holes, spaced 0.2 in. apart. Once the basket is filled with concrete, it is covered and tapped gently, then excess mortar is removed from the outside surface. The basket is dropped freely through a closed-ended pipe filled with 67 in. of clear water, as shown in Figure 11 (Appendix B). After 15 sec at the bottom of the tube, the sample is retrieved in 5 sec and allowed to drain for 15 sec before measuring its weight. The test is repeated three times for fluid concretes, and the calculated cumulative weight loss is reported as a percentage of the initial sample weight.

The washout test can be modified to yield more aggressive water erosion. For example, the number of water immersion can be increased to five times, and the basket openings can be increased to

0.8 in diameter to prevent the viscous mortar from blocking the holes (Davies 1986). In this study, the number of immersions was increased to 10 times when the washout resistance of stiff concrete was evaluated.

5.1.6 Other Tests The susceptibility of different concretes to bleed can be examined using standard tests such as ASTM-C 232 or CRD-C 9. Bleeding water is collected each 10 min for the first 40 min, then at 30 min intervals until no more water can be removed. The total volume of collected water is expressed as a percentage of the available water in the mix. The setting time of the concrete can be measured using the Proctor Penetration test (ASTM-C 403 or CRD-C 86). The stiffening rates should be monitored at ambient temperatures similar to those expected in the field.

The temperature rise of the concrete can be roughly measured by inserting a thermocouple inside a well insulated concrete specimen and monitoring temperatures over time. This is not the same as measuring the adiabatic heat rise, but it can be accurate enough to estimate the heat rise in relatively thin repair slabs. The pH and turbidity of water can be calculated after pouring a constant weight of fresh concrete through a predetermined height and volume of clear water. Such measurements can be employed for selecting types and optimum concentrations of AWAs that are needed to reduce turbidity and preserve water quality.

5.2 Testing for Mechanical Properties

5.2.1 Abrasion Resistance Figure 12 (Appendix B) shows a test apparatus developed by Liu (1980) to compare the resistance of different concrete mixtures to abrasion-erosion (CRD-C 63). The wear damage caused by waterborne debris in swirling waters is simulated by employing 70 steel balls of various sizes. An immersed agitation paddle rotates causing the water to circulate at a 6 ft/sec velocity. Cylindrical test specimens measuring approximately 11.75 in. in diameter and 4.5 in. in height are used. The concrete disks are tested for 72 hr and weighed every 12 hr to determine weight losses.

The cumulative weight reduction of concrete placed and thoroughly compacted above water should be compared to those cast under water. The method adopted in this study consisted of casting concrete

from a hand scoop into the disk mold through 12 in. of water. Fluid concretes were not consolidated under water, whereas stiff concretes were poured in four lifts that were compacted using a small trowel. The basin containing the mold was then dewatered, and the top surface of the disk was struck flat (Figure 13, Appendix B). The cumulative weight loss of the concrete was determined by testing the bottom surface of the specimens which is believed to be more representative of the material's wear resistance than the upper face.

It is important to note that the underwater abrasion test is an accelerated test which does not reflect the actual shape, weight and hardness of transported sediments that may be encountered in reality. Therefore, the results are hardly suitable for making predictions regarding quantitative magnitude of abrasion damage. Moreover, the 6 ft/sec water velocity in the test basin is not sufficient to frequently cause the steel balls to be suspended. Hence, the prevailing mode of damage is believed to be caused by grinding and not by a combination of grinding and impact. Therefore, this test is not quite suitable for addressing the resistance of concrete to combined abrasion and impact damage. This is especially important since recent studies have indicated that repetitive impact forces acting on very tiny areas are the principal cause of abrasion damage.

5.2.2 Strength A concrete block can be cast under water by allowing fresh concrete to fall through a determined height of water in a placement box. Consecutive layers can be cast to observe flow patterns, bond developments between different lifts, etc. It is advisable to add a coloring agent to subsequent lifts to differentiate between them. The concrete should be cured in water, then recovered to examine its surface for honeycombing, segregation, laitance and flow around preplaced obstacles. The block should be cored to measure the in-place density and strength of the concrete. Such results should be compared to values obtained from standard cylinders prepared above water.

5.2.3 Bonding The development of bonding between underwater-cast concrete and hardened horizontal or vertical surfaces can be evaluated using a point-load tensile test (Figure 14, Appendix B) (CRD-C 85). The bond strength is calculated as the ultimate failure load divided by the square of the core

diameter. Important parameters, such as the need of removing laitance and sedimentation from the surface of freshly-cast concrete prior to casting a subsequent lift can be determined for various concrete mixtures using this test.

The pullout bond test (ASTM-C 234) can be used to compare and select effective admixtures that can enhance the bonding between underwater-cast concrete and steel bars. In this research, the bond developments between various concretes and vertical steel bars were evaluated to determine the effect of AWA on preserving the integrity of underwater-cast concrete. A 6 in. standard mold, with a vertical steel bar embedded in the middle, was placed in a box filled with 12 in. of water. Fluid concrete was dropped inside the mold without compaction. The basin was then drained, and the surface of the concrete was stuck flat. Concrete was also cast and compacted above water to measure the bond developments between steel and dry-cast concrete and compare them to those measured for the underwater cast concrete.

CHAPTER SIX

CONCRETE MAKING MATERIALS

6.0 Introduction

The composition, contents and properties of aggregates and cementitious materials have a direct bearing on the final quality of underwater repair surfaces. A number of specifications of these ingredients are presented below.

6.1 Aggregate

The durability and strength of the hardened concrete is influenced by the texture, shape, hardness, gradation, grain size, chemical composition and degree of weathering of the aggregate in use. The aggregate should not be alkali reactive or contaminated with any substance that may impair the concrete durability. Aggregate should be hard and free of impurities such as silt, mica and harmful organic matters which can prevent good bonding with the cement paste. Hard coarse aggregate such as basalt, chert, traprock, granite, quartz or diorite should be used. Fine aggregate should consist of hard sand or crushed stone screened free of dust, silt, clay and other impurities.

The choice between angular and rounded coarse aggregate is partially dependent on the required consistency of the fresh concrete. Whenever high fluidity is desired, it is recommended to use rounded aggregate with minimal amounts of flattish or flaky particles. Such aggregate can reduce the water demand and improve the workability of the concrete. Angular aggregate can increase the water demand or compaction effort required to achieve similar consistency to concrete made with natural rounded gravel. Well graded crushed rock of the types listed may be used when stiff and highly washout-resistant concrete is cast and compacted under water.

Well graded aggregate should be employed to enhance the consistency and cohesiveness of the concrete since gap grading can increase bleeding. The MSA depends on the segregation susceptibility

of the concrete, which is influenced by the placement method. In general, 3/8 to 3/4 in. MSA should be used for underwater repairs since such aggregate can improve the rheological properties of the concrete and can also enable the filling of small repair areas.

Fine particles bring about cohesion in fresh concrete however, an excessive amount of fines can sharply reduce fluidity. The coarse aggregate should have less than 5 percent of its particles passing the No. 8 sieve. The sand should be graded from coarse to fine with more than 95 percent passing the No. 4 sieve but less than 5 percent passing the No. 100 sieve (Li 1959). Fine materials such as quartz powder or pozzolan should be added to compensate for any lack of fines. The optimal content of fine aggregate depends on the required rheological properties. For example, pumped concrete is more prone to segregation than tremie concrete and should contain a greater amount of fines. It is important to note that an excessive addition of sand can increase the water demand without further improvement in cohesive strength. The optimal sand content for underwater-placed concrete depends on the materials in use and the desired workability and is usually 45 ± 3 percent for high consistency concretes.

The effect of sand content on strength and washout resistance was investigated in the Netherlands by allowing three concrete mixtures with 35, 40 and 45 percent sand contents to fall through 6 in. of water. Cubical specimens were then cut from the hardened concrete blocks and tested for strength. The crushed concrete was then heated and sieved to separate dry constituents and determine the amount of cement loss (Netherlands CUR 1973). The three concretes had similar amounts of cement loss and similar relative strength values. Slightly favorable results were obtained with the 40 percent sand mix.

6.2 Cement

The underwater repair of eroded slabs may involve the placement of large volumes of concrete. Therefore, the heat rise should be controlled since sharp thermal gradients can induce high stresses that can lead to cracking. This is especially critical for highly-restrained thin repair slabs.

Submerged concrete is permanently in contact with water and may be subjected to soluble aggressive substances, such as sulfates. A Type II cement is recommended because of its moderate heat generation and moderate resistance to sulfate attack. However, if the risk of sulfate attack is high, a Type V cement or a blast furnace slag should be used instead.

The cement content should not be more than what is normally needed to achieve the required strength and abrasion resistance. Fine fillers can replace some of the cement that is not needed for strength development. ASTM-C 593 recommends that the particle size of filler complies with a maximum residue of 2 percent on No. 30 sieve and a maximum residue of 30 percent on No. 200 sieve, by weight. In order to improve the rheological properties of the fresh concrete, it is also important to have approximately 760 lb/yd^3 of cement and other fines that are smaller than the No. 50 sieve. Furthermore, the content of fines passing the No. 100 sieve should be approximately 650 lb/yd^3.

6.3 Admixtures

Several important concrete properties necessary for securing durable underwater repairs may not be obtained merely by proper material selection and mix proportioning without adversely endangering other properties. Fortunately, newly-developed admixtures can be used to improve various concrete characteristics without endangering other desirable properties. Among these additives are pozzolans, surface-active agents, AWAs, steel fibers and polymers.

6.3.1 Pozzolans Pozzolans include natural materials such as tuffs as well as artificial materials such as fly ash and silica fume. Extra fines provided by pozzolanic materials can improve the consistency, stability and washout resistance of the fresh concrete. Suitable pozzolans can be used to replace part of the high cement content normally needed for underwater casting, thus reducing cost and temperature related problems. Moreover, pozzolanic reactions produce cementing materials that reduce the porosity of the hardened concrete, hence improving its resistance to wear damage, resistance to sulfate attack, permeability of harmful substances, adhesion and strength.

Silica fume exhibits the greatest benefits for enhancing strength and wear resistance of concrete. The tiny silica particles react with calcium hydroxide and water and result in hydration products that toughen the cement matrix and improve the quality of the interface between the aggregate and the hydrated cement paste. As a result, the wear resistance and strength of the concrete, as well as its bonding to neighboring repair surfaces and reinforcing steel, are improved. The incorporation of silica fume increases the water demand and can result in a harsh mix. Therefore, WRAs or HRWRAs should be incorporated to maintain good workability without increasing the water content. Both silica fume and AWAs increase the water demand, therefore, a balance between these two additives should be achieved. The silica fume content should not exceed 15 percent of the weight of cementitious materials in order to avoid high concentrations of water reducers which can lead to excessive set retardation and bleeding.

Unlike silica fume, when fly ash is employed as a replacement for some of the cement, the amount of water needed to provide a certain level of fluidity is usually reduced. Fly ash replacing up to 50 percent of the cement weight was recommended for massive underwater tremie placements (Gerwick et al. 1981). Such concretes were reported to be self-leveling and cohesive enough to reduce segregation and laitance formation.

Blast furnace slag is usually used as a replacement for a percentage of the cement weight, such as 70:30 slag to cement ratio. The fineness of blast furnace slag should not be much greater than that of portland cement to prevent excessive heat rise. High contents of fly ash or blast furnace slag can be used in concrete intended for filling deep and massive scour holes under water. A silica fume concrete can then be cast over the filled hole to provide a hard and durable overlay.

6.3.2 Surface-Active Admixtures Surface-active admixtures that are of a considerable importance for subaqueous concretes are HRWRAs, WRAs and AEAs. Such additives can reduce the internal shear resistance of plastic concrete, thus improving its ability to spread and self-level. Regular WRAs are suitable for tremie concretes. However, whenever an AWA or silica fume is incorporated, the dosage

of a WRA that is required to maintain the desired fluidity may exceed the manufacturers' maximum recommended dose by two to three times, thus leading to excessive delays in stiffening. Therefore, a HRWRA should be used to secure high mobility. Regularly, a HRWRA has an active slump period of 30 to 60 min, followed by rapid fluidity loss. However, new HRWRAs, such as Sikament 86 or Rheobuild 1000, should be employed since they can reduce the degree of fluidity losses. However, such HRWRAs may contain retarders that can delay the setting when used at high concentrations.

Closely-spaced air bubbles improve the freeze-thaw durability of concrete which may be desirable in lock chambers, spillway aprons, hydraulic channels, etc. The entrainment of approximately 4 percent air volume can also improve the workability and cohesiveness of fresh concrete. Williams (1959) reported that the cohesiveness and inplace strength of tremie concrete was improved when a retarder and an AEA were incorporated. The volume of laitance deposited on the surface of tremie concrete which incorporated both a retarder and an AEA was approximately 5.6 and 3.8 times less than that of plain and air-entrained concretes, respectively. Similarly, the average f'_c of this concrete 4 ft from the discharge location was 8 percent less than that near the entry point, whereas the other two mixtures suffered 35 percent strength reductions.

6.3.3 AWAs AWAs are incorporated to enhance the resistance of fresh concrete to water erosion, segregation and bleeding. The majority of AWAs consist of water-soluble polymers, although different types of AWAs also exist. Ramachandran (1984) categorized AWAs and thixotropic additives into five classes, of which three are most relevant to underwater concrete:

- Class A. Water-soluble polymers, such as cellulose-ether derivatives which increase the viscosity of the mixing water.
- Class D. Inorganic materials of high surface area, such as silica fume and bentonite.
- Class E. Inorganic materials that increase the content of fine particles in concrete, such as fly ash and natural pozzolanic materials.

The other two classes are water-soluble organic flocculants and emulsions. These substances consist

of different organic materials which can enhance the viscosity of the cement paste by increasing inter-particle attraction between cement particles. Class D and E products include pozzolanic materials that absorb some of the mixing water, thus reducing the migration of free water within the fresh concrete. AWAs considered in this report belong to Class A. Kawai (1987) classified water-soluble polymers of Class A as follows:

A. Natural polymers. These include starch, natural gums and plant protein.

B. Semi-synthetic polymers. These include decomposed starch and other starch derivatives; cellulose-ether derivatives, such as hydroxy propyl methyl cellulose, hydroxy ethyl cellulose, hydroxy cellulose and carboxy methyl cellulose; as well as electrolyte, such as sodium alginare.

C. Synthetic polymers. These include ethylene, such as poly ethylene oxide; and vinyl, such as poly vinyl alcohol.

Water-soluble polymers form glue-like gels that bind excess water in fresh concrete, thus increasing the water retentivity of the concrete and reducing bleeding, segregation and water erosion. Concrete containing an AWA is usually sticky due to the lack of extra water needed to fluidize it. Manufacturers recommend using W/CMs in the range of 0.45 to 0.60. However, lower W/CMs should be adopted to produce wear-resistant concrete, therefore, a WRA or HRWRA should also be incorporated. Providing that enough water reducers are provided, the mobility and plasticity of the concrete is usually enhanced in the presence of an AWA, especially when the concrete is harsh or lean. The flow of a fluid concrete incorporating an AWA proceeds at a slower rate than a concrete with a comparable fluidity that does not contain an AWA.

Several AWAs tend to delay the initial setting time of concrete, and as such, they should be combined with a high dosage of WRA or HRWRA that contain a retarder. Several proprietary AWAs are formulated to incorporate HRWRAs and retarders. Some AWAs can entrap as much as 15 percent excess air, therefore, de-airing additives must be employed to expel the extra air in order to enhance concrete strength and durability.

Kawai (1987) compared the ability of nine different water-soluble polymers to reduce segregation. The muddiness of water was measured after a constant volume of mortar had fallen through it. All mortars had a fixed W/CM of 0.5. The hydroxy propyl methyl cellulose, hydroxy propyl cellulose and poly ethylene oxide seemed to be most effective in reducing water erosion. They did not gel upon mixing with water, however, they entrapped large volumes of air.

Several additives, including natural gums, synthetic polymers, surface-active admixtures and inorganic powders which can improve the washout resistance of fresh concrete were evaluated (Netherlands CUR 1973). The type and content of aggregate were the same for all concretes, and the cement content was fixed to 632 lb/yd^3. Admixture doses were adjusted to yield approximately 5 in. slump values and 5 percent air volumes. Freshly-mixed concrete was dropped 6 in. through water. A sample of the underwater-cast concrete was then removed to measure the in-place density and strength and compare them to standard values obtained from dry-cast specimens. Another sample was retrieved from the water, oven-dried and sieved to determine the amount of cement eroded by water. Concretes incorporating methyl cellulose polymers exhibited the best washout resistance and suffered the least strength reduction. Surface-active agents showed good washout resistance levels, especially when an AEA and a retarder were jointly used.

In another study, concretes containing different types of AWAs were compared to a conventional high quality concrete. Fresh concrete was dropped through 22 in. of water and was not consolidated in place. Laitance development and flow around obstacles and reinforcing bars were observed. The hardened concrete was cored to compare the strength of the underwater-cast concrete to that of concrete placed above water. Mix proportions of some of the investigated mixtures, in lb/yd^3, are presented below (Maage 1984).

AWA Type	(Control)	Rescon T	Complast
Cement (10% Fly Ash)	610	755	521
Silica Fume	61	75.5	52.1

3/4 in. MSA	1,446	1,177	1,234
Fine Sand (1-8 mm)	246	200	211
W/CM	0.42	0.50	0.62
WRA	7.13	--	--
HRWRA	7.13	--	--
AWA	--	24.9	1.55

A proprietary prepackaged mortar, Hydrocrete, was also employed. Hydrocrete was believed to have a W/CM of 0.35 and contain approximately 1,265 lb/yd^3 of cement, 1/4 in. MSA aggregate and a HRWRA. The reported properties were as follows:

AWA Type	(Control)	Rescon T	Complast	Hydrocrete
Slump, in.	9	9.5	8.25	10.75
Flow Spread, in.	16.5	17.75	12.5	20
Fresh Density, lb/yd^3	152.9	1,42.9	134.2	139.8
Air, %	1.8	2.3	12.2	3.5
28 day f'_c, psi	10,340	7,570	4,570	8,090
f'_c (Water/Air)	0.18	0.80	0.56	0.87
Mud Thickness, mm	15-40	0	2-5	0
Surface Slope, deg	2.4	2.4	16.7	1.9

The above results show that some AWAs can greatly enhance the resistance of concrete to water erosion and reduce laitance formation and sedimentation.

6.4 Steel Fibers

Concrete incorporating steel fibers has been used on a number of hydro-technical rehabilitation projects to repair eroded concrete surfaces. The majority of these repairs were carried out on land since fibrous concrete does not meet the high fluidity requirements of tremie-placed or pumped concretes. However, if properly proportioned, stiff and highly viscous fiber-reinforced concrete can be

deposited under water by closed buckets or skips where the material is then spread and compacted in place (Chapter Ten).

The addition of steel fibers has been reported to improve the impact resistance, flexural and tensile strengths, ductility and strain capacity as well as the fatigue endurance of hardened concrete. Well anchored and randomly dispersed fibers tend to stitch chipped pieces of concrete to the main slab, thus reducing the surface irregularities and decreasing the rate of cavitation damage. In general, the wear resistance of fibrous concrete increases with the reduction of W/CM and increase in strength. The use of 1/2 versus 1 in. long steel fibers added in similar quantities was reported to have a small effect on the wear resistance of the concrete (Liu et al. 1981). There are mixed opinions about the resistance of steel fibrous concrete to abrasion-erosion. Field observations of several hydraulic structures that are subjected to high discharge velocities confirm that fibrous concrete is capable of reducing the rate of wear damage. For example, an 18 in. fibrous concrete overlay was placed over spillway deflectors in the Lower Monumental Dam spillway in Washington. The concrete was reported to contain 850 lb/yd^3 of cement and 220 lb/yd^3 of 3/4 in. long steel fibers. The W/CM was 0.39, and the 28 day flexural strength was 750 psi (Hoff 1975). The repair was inspected after two seasons of operation and was found to be free of visible erosion.

Fibrous concrete containing 3/4 in. MSA and 120 lb/yd^3 of 1 in. steel fibers was used to cast a 15 in. overlay over the stilling basin slab of the Dworshak Dam in Idaho. The concrete had a W/CM of 0.41 and developed a f'_c of 8,000 and a 1,000 psi flexural strength after 28 days of curing. Half of the repair area was impregnated with polymer. A partial inspection of the basin which was conducted a year after the repair confirmed that the fibrous overlay performed well, with the impregnated side of the slab showing slightly better behavior than the non-impregnated one.

The 12 in. fibrous concrete overlay used to protect the stilling basin in Kinzua Dam did not perform well. The repair mix contained 750 lb/yd^3 of cement and 1 in. steel fibers which was added as 2 percent of the concrete volume. The W/CM was 0.40, and the average 28 day f'_c was 6,000 psi.

Scour holes of 42 in. maximum depth were discovered after 3 years of operation. The poor behavior of fiber-reinforced concrete was confirmed by testing cores for underwater abrasion where the weight loss after 72 hr of testing was 9.4 percent (Holland 1983). Other laboratory studies confirmed that fibrous concrete can provide less wear resistance than conventional concrete (Liu and McDonald 1981).

Since added fibers usually replace some of the volume occupied by coarse aggregates, which are largely responsible for resisting abrasion-erosion, it is reasonable to expect slightly lower wear resistance when fibers are incorporated. Once abrasion damage proceeds, the exposed steel fibers are believed to vibrate resulting in stress concentration fields around the fibers. This can result in a progressive deterioration of the interface between the cement matrix and fibers that can cause the fibers to pull out and pull adjoining concrete pieces with them.

Providing that the steel fibers are properly anchored, their presence should enhance the impact resistance of concrete. Therefore, the enhancement of bonding between the steel fibers and the cement paste is believed to be essential to minimize abrasion damage and secure high toughness and impact resistance values. Sound bonding between the cement paste and steel fibers could be achieved by using rich concrete which incorporates silica fume. Similarly, the use of fibers with a rough surface texture, or long and deformed fibers could enhance the adhesion and anchorage to the cement matrix. However, fiber-reinforced concrete is not recommended until these problems have been fully resolved.

6.5 Polymers

Polymer-impregnated concrete, polymer portland-cement concrete and polymer concrete exhibit superior strength and resistance to abrasion and cavitation damage than those of portland cement concrete. However, polymers are relatively expensive and require high quality control because of their complicated batching, curing and possible health hazards. Their use is mainly limited to patching small damaged areas because of their high premium cost, fast setting characteristics and difficulties in binding to damaged surfaces under water.

The surface energy of most epoxies is more compatible with that of water than that of concrete. Consequently, most epoxies tend to bead up and may not secure sound bonds in the presence of water. Recently, new polymer products that can be used for underwater applications have been developed. For example, Adhesive Engineering Company developed a three component epoxy grout system, Con-cresive AEX-1533 G/Fine, that contains 17.5 percent liquid epoxy binder by weight, a curing agent, and small size aggregate. The epoxy grout can be pumped and is claimed to develop excellent bond strength to concrete and steel surfaces, however, it has a limited pot life of 35 minutes. It is suggested that a stronger bonding with repair surfaces can be secured when the grout system is delivered under water through a pipe or a pump line, then consolidated into place (Adhesive Engineering Company 1984).

Shell Chemical Company also introduced two quick-setting epoxy resin concrete products, Shell Joint Fill RC 1000 and HD 5000. These materials set-up and bond well under water, however, their pot lives are limited to 3 minutes. These products are strain-compatible with concrete and are reported to exhibit excellent bond strength and toughness. The 72 hr weight loss of RC 1000 and HD 5000 tested less than 0.05 and 0.5 percent, respectively (Shell Chemical Company 1983).

Polymers can be employed in the fabrication of precast panels which can be cast and cured above water, then guided through water to the base of stilling pools where they can be anchored to underlying materials and grouted together. Whenever polymer concrete is used to fabricate such modules, the coarse aggregate in use should be more durable than the binder itself and should be free of moisture in order to prevent decay in strength and durability. Whenever aggregate cannot be dried, a silane-coupling agent may be used to improve the bond of the monomer system to the wet aggregate (Fontana et al. 1985).

The underwater abrasion test has been utilized to evaluate the relative wear resistance of several concrete polymer materials. The 72 hr weight losses of the methyl methacrylate polymer concrete, polymer-impregnated and polymer portland-cement concretes were approximately 2.1, 2.8 and 5.2

times greater than that of a vinyl ester polymer concrete, respectively, which had a weight reduction value of 0.8 percent (Liu 1980). The wear resistance of polymer-impregnated concrete was compared to those of plain and fibrous concretes. The former exhibited approximately 65 percent and 50 percent less weight loss than conventional limestone concrete and silicious gravel fibrous concrete, respectively. Polymer-impregnated fiber-reinforced concrete maintained twice the wear resistance over plain fibrous concrete (Liu 1980).

Polymer-impregnated concrete was used to repair several eroded hydraulic facilities. For example, the stilling basin at the Dworshak Dam was covered with a 15 in. fibrous concrete overlay that was partially impregnated in the dry. The monomer system consisted of 37 percent methylmethacrylate, 2.5 percent cross agent and 0.5 percent catalyst. At the conclusion of a 6 hr soak period, the monomer was polymerized by steam heating. In general, polymerization occurred at a depth of 1.5 inches. Laboratory tests indicated that the polymerized fibrous concrete attained f'_c values in excess of 20,000 psi (Murray et al. 1977). An initial underwater inspection showed that the concrete was sound, except for some wear damage at the joints that appeared to have been wet during impregnation. Subsequent inspection revealed that the impregnated concrete had suffered severe spalling. The polymerized concrete surface seemed to have prevented the internal moisture in the concrete from migrating outward at freezing temperatures. Therefore, the freezing of the internal water led to expansion and subsequent spalling.

CHAPTER SEVEN

EVALUATION OF FLUID CONCRETES FOR REPAIRING SMALL AND RELATIVELY SHALLOW SCOUR HOLES

7.0 Scope of Experimental Work

Fluid concretes suitable for repairing small and relatively shallow (1 to 3 ft deep) scour holes should possess the following characteristics:

A. Lasting high workability to flow readily and self-compact.

B. High cohesive strength to minimize segregation and bleeding.

C. High resistance to water erosion.

D. High resistance to abrasion-erosion.

This chapter summarizes the results of two sets of experimental investigations that were undertaken to develop concrete mixtures which can secure good balance among the above desired properties. The first series of tests aimed at optimizing mix proportions and identifying compatible additives that can enhance the quality of underwater repair concretes. Several admixtures capable of improving material performance were incorporated in different quantities and combinations. A total of 54 trial mixes were prepared and approximately 1,000 laboratory tests were conducted to identify promising fluid mixtures that can be employed to repair relatively shallow scour holes under water. The significance of alternative concrete materials and proportions, including types and dosage rates of mineral additives, AWAs, surface-active admixtures, water contents as well as aggregate contents were evaluated. Properties evaluated in these trials included fluidity, setting time, likelihood of water erosion and f'_c.

In the second series of tests, 11 concretes were selected from the trial mixtures to evaluate properties critical to good performance in field applications. The concretes differed in the type and amounts of mineral and organic admixtures used, types and concentrations of AWAs and W/CMs. Among the

rheological and mechanical properties that were evaluated were several measures of initial workability and its retention over time at different service temperatures, setting times at these temperatures, loss of materials due to intermixing with water, susceptibilities to bleeding and segregation, temperature developments, bond strengths, and abrasion resistance, as well as compressive, tensile and flexural strengths. Approximately 1,100 tests were performed.

7.1 Materials

The chemical and physical properties of a Type I/II portland cement that was employed throughout this research are summarized in Table 2 (Appendix C). A powder silica fume and a Class F fly ash were also employed, their chemical compositions are listed in Table 3 (Appendix C). Natural river bed sand and gravel were employed, their gradations are illustrated in Figure 15 (Appendix C). The physical properties and lithography of the gravel are summarized in Tables 4 and 5, respectively (Appendix C).

Table 6 (Appendix C) presents the types and properties of the employed admixtures. Three American-manufactured AWAs and two European products were investigated, most of these AWAs are still in the development stage. The Kelco AWA is a natural polymer, whereas the Protex, Master Builders and Rescon AWAs are synthetic cellulose-based products. The Z10-A material (Concrete Hitech Ltd, 1986) is an amalgam of 22 different chemicals originally developed to improve the durability of concrete against sulfates. It was employed for its merits in reducing segregation and bleeding.

All tested HRWRAs are based on melamine-sulfonic acid formaldehyde condensates because naphthalene based HRWRAs were found to be incompatible with some AWAs [such as cellulose and polyethylene oxide AWAs (Neeley 1988)]. Modified Type D ASTM-C 494 WRAs containing lignosulfonic acids were incorporated in some mixtures. A de-air agent was added whenever the incorporation of an AWA resulted in entrapping an excessive volume of air. When air was not entrapped, a vinsol resin AEA was used to secure the desired air content, whenever needed.

7.2 Mixing Procedures and Test Methods

Trial mixes that were evaluated in the first series of tests were prepared as 0.40 to 0.55 ft^3 batches, whereas mixtures investigated in the second test series were batched in four 1.8 ft^3 batches. The adopted mixing procedure consisted of charging the sand and pea gravel first in an open-type pan mixer, then adding one third of the mixing water to wet the aggregate surface. Silica fume, fly ash, blast furnace slag and AWA were blended by hand with the cement then added to the wetted aggregate. Another third of the mixing water was then introduced. The rest of the water was used to dilute aqueous admixtures which were introduced separately to the wet concrete. After the addition of all concrete ingredients, the concrete was mixed for 3 min, which was followed by a 3 min rest period and an additional 2 min of mixing.

Several of the tests described in Chapter Five were employed to evaluate relevant physical and mechanical properties of the 54 trial and 11 final mixtures. A summary of these tests is presented in Table 7 (Appendix C). All tests were performed in compliance with their specifications (Chapter Five) and were conducted by the same individual to minimize operator errors. All mixtures were cast and tested at approximately temperatures of 65 ± 5°F, unless otherwise specified. Specimens prepared for measuring mechanical properties were stripped one day after hardening then stored in a curing room (73 ± 3° F, 97 ± 3 percent relative humidity).

7.3 Test Series I - Material Evaluation and Mix Optimization

Achieving optimal performance with the fresh and hardened concrete requires a careful selection of concrete constitutes and balanced mix proportions. An extensive program was undertaken to determine the type and contents of concrete-making materials and additives needed to secure the desired concrete properties. A total of 54 trial batches were evaluated to achieve the following:

A. Select effective and compatible surface-active additives and determine required concentrations necessary to achieve the desired workability, without causing long delays in setting times.

B. Determine the maximum allowable contents of sand and other fines needed to enhance stability.

C. Determine balanced concentrations of pozzolans and AWAs to prevent excessive increase in water demand.

D. Develop promising repair mixtures for further laboratory evaluation. Mix proportions of the trial mixtures are summarized in Table 8 (Appendix C), along with the measured slump, flow, unit weight, air content, setting time and f'_c values. Among the findings were:

7.3.1 Cementitious Materials Unlike conventional wear-resistant concretes, the cement contents of underwater repair mixtures were reduced to prevent temperature related problems. A Type I/II portland cement was used to reduce the heat of hydration and permit the use of lower doses of surface-active additives. Except for a few concretes containing high concentrations of blast furnace slag or fly ash, the cement content ranged between 560 and 610 lb/yd^3. The total weight of the cementitious materials was fixed at approximately 670 lb/yd^3.

All mixtures, except one, incorporated silica fume to enhance the cohesiveness, abrasion resistance and bond development of the concrete. The added silica fume content varied from 4 to 15 percent of the cement weight. The addition of small amounts of fly ash seemed to increase the volume of fine materials and enhance the workability and cohesiveness of fresh concrete. The fly ash was effective in improving the consistency of concrete containing silica fume. The optimum content of fly ash content was found to be 5 percent of the cement weight. Fly ash was not needed when blast furnace slab was employed.

7.3.2 W/CM The amount of mixing water was kept low by incorporating high doses of water reducers. However, the addition of AWAs coupled with the use of silica fume made it necessary to use relatively high water contents in order to secure the required mobility levels. The W/CM of trial mixes varied from 0.34 to 0.48. In general, W/CMs in excess of 0.40 were needed with concretes containing medium-to-high doses of AWAs.

7.3.3 Aggregate Rounded 3/8-in. MSA was employed to reduce segregation, enhance strength development and enable the concrete to flow into congested and small areas. The gravel is hard, thus improving abrasion resistance. The sand content was varied between 42 to 47 percent (of the total aggregate volume) in order to find the optimal content necessary to improve rheological properties. For the type of materials used, it was determined that a sand content comprising 46 percent of the total aggregate volume was the maximum amount that can be added without substantially increasing the water demand or reducing the consistency of the concrete.

7.3.4 Surface-Active Admixtures All of the concretes incorporated a HRWRA to enhance the fluidity or decrease the W/CM. Melment HRWRA was used in the first three trial mixtures and proved to be incapable of reducing the W/CM to less than 0.40. Furthermore, it exhibited a moderate slump loss. Similar results were obtained when a double dosage of WRA was incorporated. Sikament FF was used in Mixes 4 through 10, but appeared to be unable to reduce the water content significantly. A new HRWRA (Sikament FF86, currently referred to as Sikament 86) was then employed. It proved to be effective in reducing the W/CM, retaining the slump and allowing more silica fume to be incorporated (Mixes 11 and 12).

Modified WRAs (Sika Plastocrete and Plastiment) were used in high concentrations to reduce the slump loss associated with the HRWRA (Mixes 12B and 12C). Plastiment was adopted since it proved to be slightly more effective in retaining the workability.

The air content of fresh concrete was fixed to 3.5 ± 1 percent in order to improve the cohesiveness and flow characteristics of the fresh concrete. A de-air admixture was employed to reduce the amount of entrapped air caused by some AWAs. An AEA was used to entrain the desired air volume when the AWA did not result in entrapping air. Both Grace and Sika AEA products were compared (Mixes 12 and 12B) and were found to be equally effective in entraining the desired air volume without exhibiting any incompatibility with other additives. The Sika AEA was selected for this project.

7.3.5 AWAs The use of an AWA enhanced the plasticity and cohesiveness of the concrete, however, it sharply increased the water demand. As a result, all concretes incorporated HRWRAs to maintain good fluidity. The dose of AWA, expressed as a percentage of the weight of cementitious materials, was varied to achieve a washout value of less than 5 percent after three test drops in water. The Master Builders, Protex and Rescon AWAs caused much air entrapment within the highly viscous concrete.

The addition of an AWA and a large amount of a HRWRA resulted in long delays in initial setting time. This was more noticeable when a modified WRA was also administered. For example, Mix 13 contained a relatively low concentration of an AWA and a HRWRA, and a high dosage of a WRA to enhance fluidity retention. The combined retarding effects of these three additives resulted in excessive delays in setting time (more than 30 hours). On the other hand, Mix 13B which did not incorporate any WRA had a final setting time of less than 15 hrs, however, its slump loss was sharper than that of Mix 13. Even long setting times resulted when higher doses of AWAs were incorporated along with WRAs (Mixes 14 and 15). The effect of AWAs on setting time is further explored in section 7.7.

7.3.6 Set Accelerators The set of concrete is affected by the stiffening rate, which itself affects the fluidity retention. It is desired that the stiffening of concrete be delayed until it is cast in place and subsequent lifts are deposited above it in order to avoid the formation of cold joints. It is important that freshly-placed concrete sets shortly after the completion of casting in order to reduce the risk of water erosion, especially when concrete is cast in moving water. Initial setting times of 10 to 15 hrs may be acceptable, otherwise, a set accelerator may be needed to prevent excessive delays in setting. The three evaluated set accelerators were:

a. Sika FL 161, a non-chlorine liquid additive.

b. Calcium chloride anhydrous ($CaCl_2$) powder admixture with 95 percent $CaCl_2$ concentration.

c. Calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$) powder containing approximately 76 percent of $CaCl_2$, by weight.

Mix 17A (SLAG) consisted of a 40:60 slag to cement ratio, by weight. It had a medium concentration of an AWA and a high dose of HRWRA. Its final setting time was delayed for 3 days. A high dose of Sika FL 161 managed to reduce that time to 40 hrs (Mix 17B), whereas a 2 percent of $CaCl_2 \cdot 2H_2O$ (of weight of cementitious materials) reduced the final setting time only by a few hours (Mix 17C). The addition of 0.75 percent of $CaCl_2$ proved most effective in reducing the final setting time to 9 hrs (Mix 17D). The same trend was observed with Mixes 18C, 18D and 18E.

7.4 Methods of Adding AWA's

Powder AWA can be blended by hand with the cementitious materials and added with them to the mixer. Another way of charging the AWA is to add it as a powder to freshly-mixed concrete either by itself or diluted with some cement, then extend the mixing time to break any powder-formed lumps and disperse them in the mix. The addition of the AWA as a powder may present some difficulties in commercial applications. Therefore, the AWA can be added in a slurry form. The slurry solution is prepared by mixing the AWA with part of the mixing water and/or HRWRA using a high-shear mixer to disperse the AWA into the liquid solution and eliminate unhydrated AWA. The dispersion of the water-soluble AWA allows the polymer chains to swell and hydrate prior to mixing with concrete, thus increasing the available surface area and effectiveness of the AWA.

In order to determine the effect of the method of adding the AWA on concrete properties, two identical concrete mixtures were prepared using the Kelco admixture. The first concrete incorporated a pre-hydrated AWA which was formed by blending powder AWA with water, then adding it to the wet concrete. The second concrete contained a powder AWA which was blended to the cementitious materials and added with them.

The properties of these mixtures are summarized below. The results indicate that both concretes had similar fluidity and washout resistance values, with the mixture containing a pre-hydrated AWA

showing slightly better results than the mixture containing slurry-added AWA. Concrete containing slurry-added AWA resulted in slightly denser and stronger concrete than the mixture containing prehydrated AWA. Throughout this research, the AWA was added as a powder to the cementitious materials. The merits of hydrating the AWA with water or HRWRA before adding it to the concrete, and the mechanism by which the AWA affects strength and other mechanical properties of concrete should be further investigated.

		AWA Slurry	AWA
Powder			
AWA, % of CM Weight		0.38	0.38
Initial Flow, in.		15.5	16.75
Initial Slump, in.		8.25	8
Unit Weight, pcf		147.6	147.3
Air Content, %		1.5	1.5
Washout Weight Loss, %	3 drops	0.51	0.46
	5 drops	1.27	1.19
	10 drops	2.50	2.44
Final Setting Time, hrs		21	21
7 day f'_c, ksi	#1	4.60	4.09
	#2	4.88	4.26
	#3	5.03	4.36
	Average	**4.84***	**4.24**
20 day f'_c, ksi	#1	6.76	6.39
	#2	7.36	6.39
	#3	7.21	6.44
	Average	**7.11****	**6.41**

* 14 percent greater than f'_c of the concrete containing dry-added AWA.

* 11 percent greater than f'_c of the concrete containing dry-added AWA.

7.5 Effect of AWA's on Compressive Strength

The influence of using AWAs on f'_c is investigated here after having established that the addition of AWA in a pre-hydrated form may secure higher strength than when it is added as a dry powder. Three types of concretes with W/CMs of 0.62, 0.45 and 0.30 were prepared. Each class had a control mixture without any AWA, one mixture with a powder-added AWA and another with an AWA added in a slurry form. Kelco AWA was added as 0.10, 0.25 and 0.29 percent of the weight of cement with concretes made with 0.62, 0.45 and 0.30 W/CMs, respectively. The mix proportions of the nine concretes are summarized in Table 1 along with their slump values which were kept low to minimize bleeding. Each concrete was prepared in a 0.25 ft^3 batch, and three 4 × 8 in. concrete cylinders were prepared. The specimens were stripped after two days and stored in a fog room until they were tested at 42 to 46 days of age.

The strength results are summarized in Table 2. As found in the previous section, concretes containing pre-hydrated AWAs had greater f'_c values than those having dry-added AWAs. This difference in strength was especially large (13 percent) for the low strength concrete (0.62 W/CM). The increase in strength was limited to 7 and 2 percent for concretes made with 0.30 and 0.45 W/CMs, respectively. The experiment also showed that the f'_c of moderate or high strength concretes may be reduced when AWAs are employed. For example, the incorporation of pre-hydrated and powder-added AWAs in concretes with W/CM of 0.62 resulted in enhancing the f'_c by approximately 14 and 29, respectively. However concretes with W/CMs of 0.45 and 0.30 containing dry-added AWAs suffered approximately 10 and 15 percent strength losses, respectively. These losses were 8 percent when the AWAs were added in pre-hydrated forms.

Further research is needed to investigate the mechanism affecting strength changes caused by AWAs and to determine the required type and dosage of AWA that can minimize strength reductions, if any, while providing the need washout resistance. The influence of different kinds of AWAs on the

mechanical properties of fluid concretes, which are more typical of materials used in under water repair operations, should also be evaluated.

The use of AWAs may prove to enhance the quality of transition zone between the cement paste and the aggregate thereby reducing bleeding, thus improving the tensile strength and wear resistance of the concrete. The effect of small doses of AWAs on the mechanical properties of high quality concrete should also be determined since low concentrations of AWAs may reduce strength losses.

Table 1. Concrete Mix Proportions

MIX	CEMENT LB/CYD	W/CM	SAND LB/CYD	P.G. LB/CYD	HRWRA FL OZ/100#CM	AWA % CM	SLUMP IN.
L1	425	0.62	1521	1883	25	0	1.25
L2	425	0.62	1521	1883	39	0.1	0.5
L3	425	0.62	1521	1883	39	0.1	0.5
M1	600	0.45	1359	1878	25	0	3
M2	600	0.45	1338	1871	40	0.25	1
M3	600	0.45	1338	1871	40	0.25	1
H1	700	0.3	1269	2010	45	0	1
H2	700	0.3	1267	2007	58	0.29	0.5
H3	700	0.3	1267	2007	58	0.29	0.5

Table 2. Compressive Strength Results

	W/CM = 0.62			W/CM = 0.45			W/CM = 0.30		
AGE	46 DAYS			45 DAYS			42 DAYS		
MIX	L1	L2	L3	M1	M2	M3	H1	H2	H3
	CEM.	AWA DRY	AWA WET	CEM.	AWA DRY	AWA WET	CEM.	AWA DRY	AWA WET
1	4975	5455	6125	9385	7915	8135	10190	8625	9475
2	4665	4815	6105	8875	7835	7965	10840	8875	9425
3	4635	6040	--	7860	--	--	9775	--	--
AVG	4760	5435	6115	8705	7875	8050	10270	8750	9450
%	100.0	114.2	128.5	100.0	90.5	92.5	100.0	85.2	92.0

7.6 Test Series II - Evaluation of Selected Concretes

Eleven promising concretes that can be used to repair relatively shallow scour holes under water were selected from the 54 trial mixtures. The rheological and mechanical properties which are necessary to ensure proper placability and durability were investigated. A summary of these tests is presented in Table 7 (Appendix C). Mix proportions of the 11 concretes are presented in Table 3, along with their measured unit weights and air contents. All 11 concretes contained AWAs, except the CONTROL mix which incorporated 13 percent silica fume (of the weight of cement) to achieve high cohesiveness. Balanced concentrations of silica fume were incorporated into the concretes containing AWAs. For example, the HSFLPRO mix had a high silica fume content (10 percent) and low dose of Protex AWA (0.15 percent, of the total weight of cementitious materials). Similarly, the MSFMPRO and LSFHPRO concretes incorporated medium and low amounts of silica fume (7 and 4 percent, respectively) and medium and high concentrations of Protex AWA (0.35 and 0.50 percent, respectively).

Unlike other mixtures, the SLAGMPRO concrete contained a 40:60 slag to cement ratio, by weight. Fly ash added as 5 percent of the cement weight for most mixtures. The fly ash contents of the FAMPRO and FA-NOSF concretes were 25 and 12 percent, respectively. All concretes incorporated silica fume, except the FA-NOSF mixture. The investigated properties of the final concretes are discussed below.

7.6.1 Fluidity Retention The majority of evaluated mixtures had initial slump and flow value of 10 ± 0.5 in. and 20 ± 2 in., respectively. As high as these values may seem, the addition of AWA and silica fume reduced segregation that may otherwise result with conventional concretes of such high fluidity values. Initial fluidity values were first measured 10 min after adding all of the mixing water. The concrete was then placed in a sealed plastic bucket to minimize moisture loss, then slump and flow values were monitored for 2 hours. The temperature of the fresh concrete was maintained at 65 ± 5°F. Figures 1 and 2 illustrate the slump and flow measurements over 2 hours.

The slump test reflects sharper reduction in workability than the flow test. This may be attributed to the fact that the latter test evaluates the response of concrete to external vibrating forces which partially offset the added viscosity caused by AWAs. In general, concretes containing little or no AWAs experienced sharper fluidity losses than those incorporating medium or high concentrations of AWAs. Both blast furnace slag and fly ash concretes experienced the least reductions in workability.

Greater fluidity losses can be expected when the temperature of the concrete is elevated. Concrete was prepared and tested at approximately 85°F in order to determine the additional W/CM needed to maintain the same initial fluidity as that of control concrete tested at 65°F. Fluidity losses over 2 hr were also evaluated at the elevated temperature.

As shown in Figures 3 and 4, the FA-NOSF concrete had identical initial slump and flow values and subsequent losses at either service temperatures. Other concretes which also were not sensitive to the increased temperature were the MSFMPRO, LSFHPRO and FAMPRO mixtures. The W/CM of the HSLFPRO concrete had to be increased by 0.02 to attain the same initial consistency at higher temperatures, as illustrated in Figures 5 and 6. However, once the initial fluidity was secured, the warmer HSFLPRO concrete exhibited identical fluidity retention as that of the cooler concrete.

Fluidity values of other mixtures at elevated temperatures are shown in Figures 16 - 23 (Appendix C). Figures 16 and 17 (Appendix C) illustrate that the initial flow of the warm CONTROL mix was almost reestablished by increasing the W/CM by 0.01, however, the initial slump value was not attained. A similar phenomenon was observed with the Z10-A mixture where the flow value was completely regained by increasing the W/CM by 0.01, but the resulting initial slump value was almost half that of the cooler concrete. It is interesting to note that the fluidity of the warmer RESCON concrete was slightly enhanced at the higher temperature, even though the W/CM was the same as that of the cooler concrete (Figures 22 and 23, Appendix C).

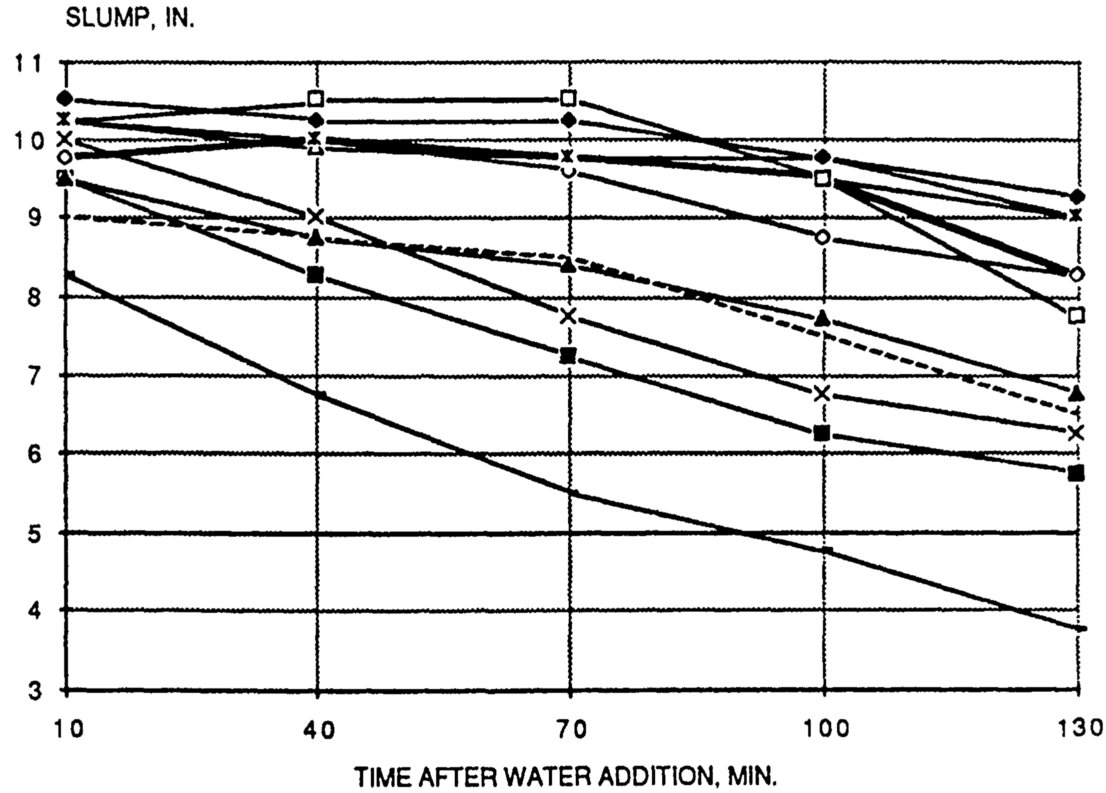
7.6.2 Resistance to Water Erosion The cumulative weight loss of fresh concrete due to water erosion were monitored 2 hours. Figure 7 compares the average washout values recorded after the completion

of mixing and 30 min later. This was done because the washout values in the first 30 min are believed to be more significant when evaluating materials for field applications. In general, the washout weight losses ranged between 1.75 and 5.5 percent of the original mass. It is important to point out that conventional concrete mixtures used for massive tremie placements may suffer as much as 15 to 20 percent mass reductions after three test drops in water.

Table 3. Summary of Final Mix Proportions

DESIGNATION	CEMENT	MINERAL ADDITIVES			TOTAL CM	W/CM	AGGREGATE	
		SF	FA	SLAG			SAND	P.G.
	PCY	% OF CEMENT WT.			PCY		PCY	
CONTROL	568	13	5	0	671	0.36	1398	1662
HSFLPRO	580	10	5	0	667	0.38	1385	1647
MSFMPRO	595	7	5	0	666	0.42	1354	1610
LSFHPRO	615	4	5	0	670	0.46	1327	1577
MSFMMB	597	7	5	0	668	0.45	1341	1590
SLAGMPRO	373	12	0	66.7	666	0.43	1322	1571
FAMPRO	499	8	25	0	664	0.42	1345	1599
FA-NOSF	689	0	12	0	772	0.41	1280	1522
RESCON	599	7	5	0	671	0.44	1343	1598
KELCO	595	7	5	0	666	0.46	1329	1581
Z10-A	600	13	5	0	708	0.36	1332	1584

DESIGNATION	ADMIXTURES FL OZ/100# CM				AWA		CACL2	UNIT WT.	AIR VOL
	HRWRA	WRA	AEA	DE-AIR	% CM	TYPE	% CM	PCF	%
CONTROL	25	5.5	1	0	0	0	0	147.6	3.25
HSFLPRO	27	5	0	0.1	0.15	PROTEX	0	147	4
MSFMPRO	34	0	0	0.13	0.35	PROTEX	0	145.9	4
LSFHPRO	33	0	0	0.17	0.5	PROTEX	0	144.4	3.5
MSFMMB	38	0	0	0.16	0.85	M. BUILD.	1.25	145.2	3.5
SLAGMPRO	36	0	0	0.15	0.35	PROTEX	0.5	143.1	4.75
FAMPRO	34	0	0	0.11	0.35	PROTEX	0	144.2	4.5
FA-NOSF	32	0	0	0.09	1.25	M. BUILD.	0.75	145.1	3
RESCON	42	0	0	0	2.5	RESCON	0.5	146	2.5
KELCO	48	0	1.25	0	0.28	KELCO	0	145	3
Z10-A	28	5.5	1	0	7	Z10-A	0	146.2	2.5



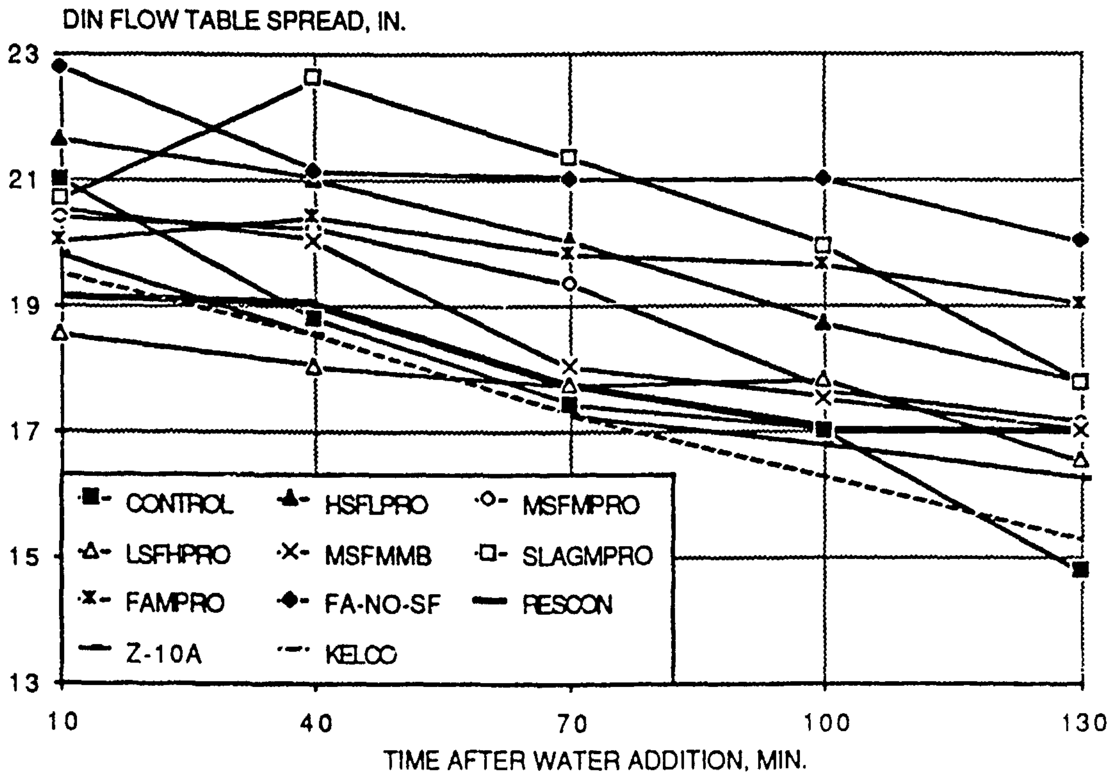
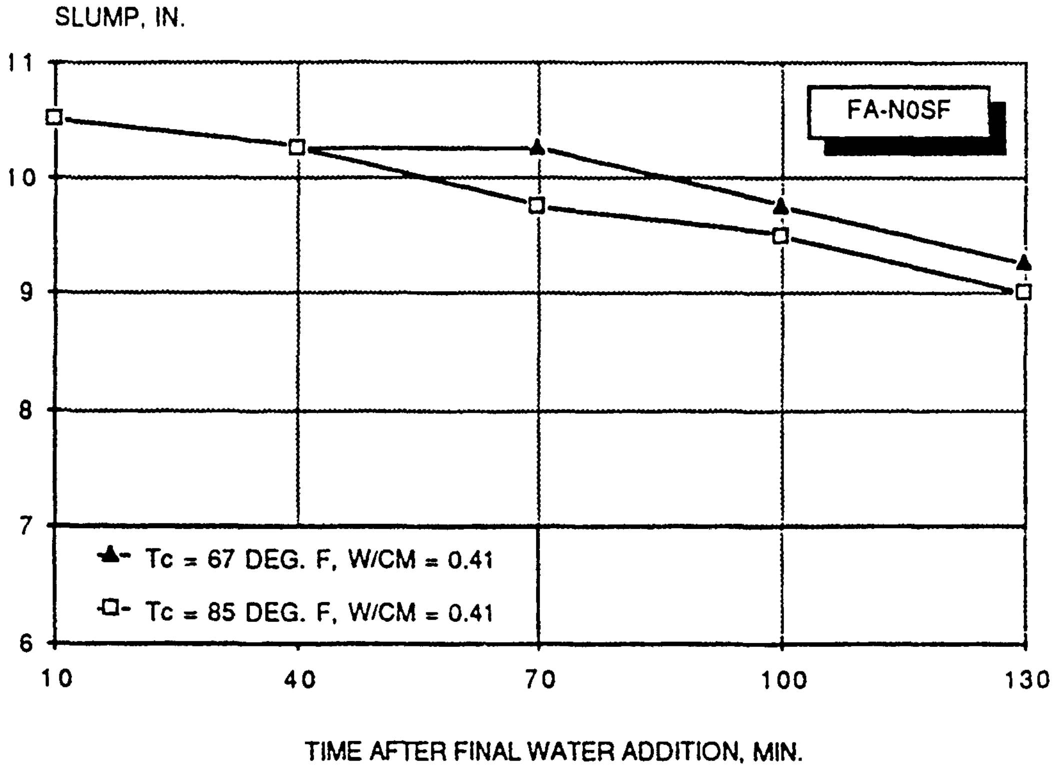


Fig. 1, 2--Slump and Flow Retentions of Final Fluid Concretes



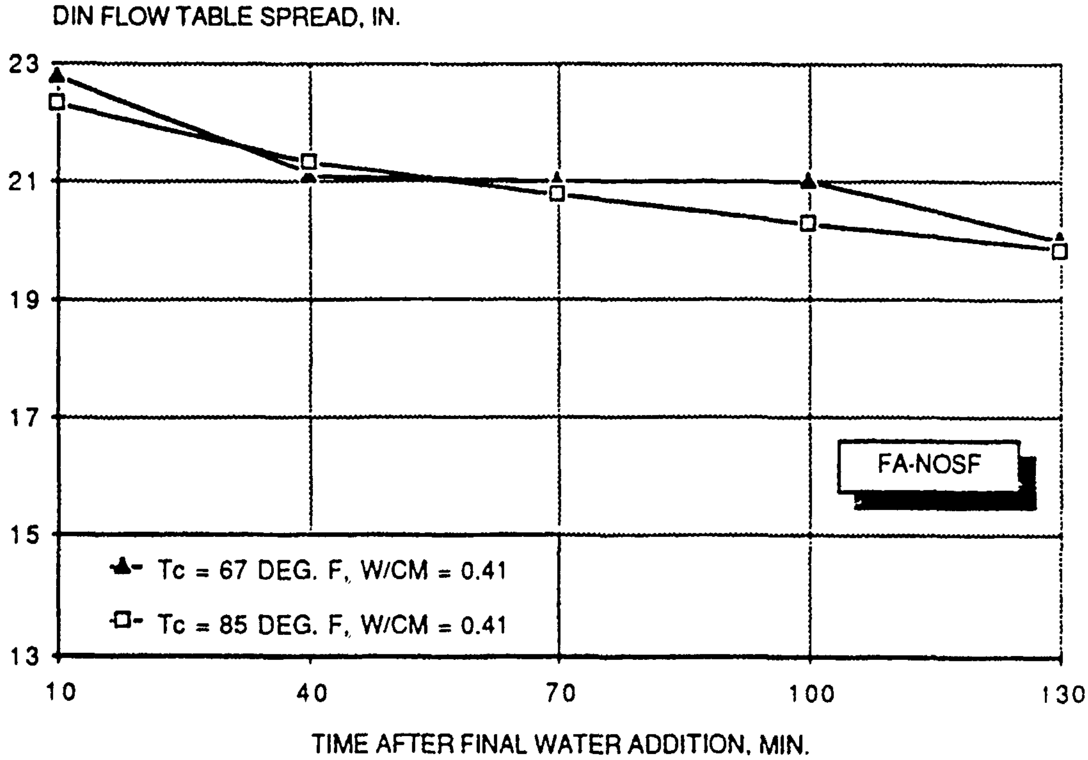
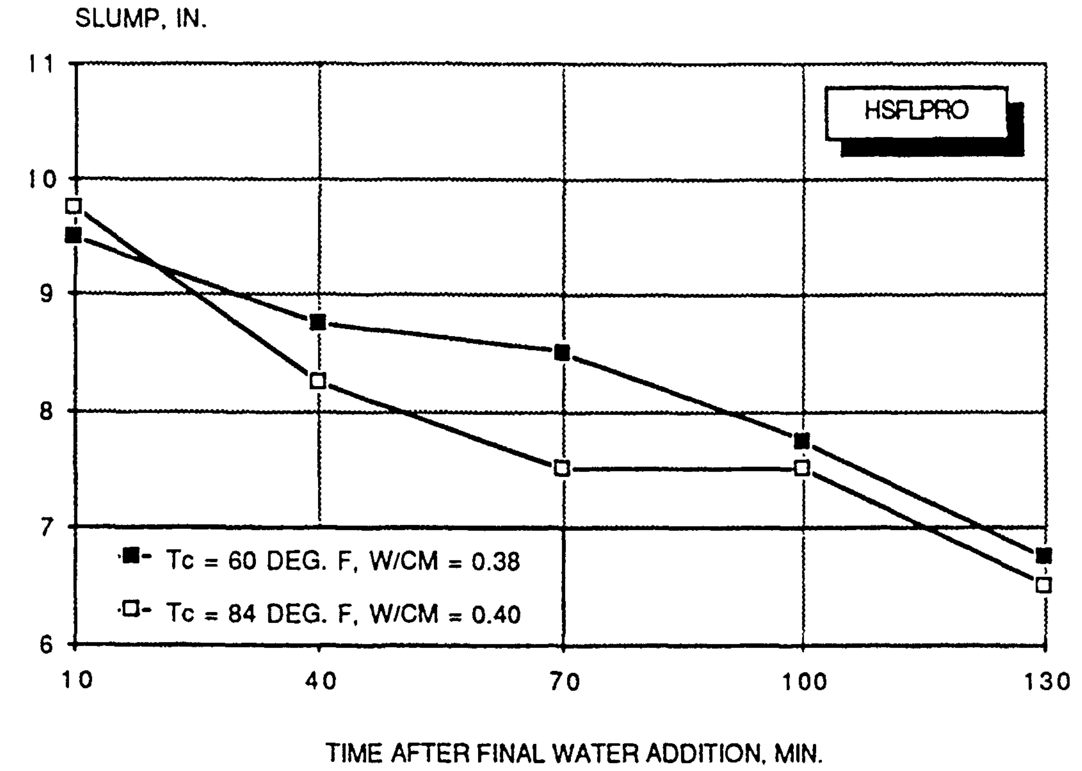


Fig. 3, 4--Slump and Flow Retentions of FA-NOSF Mix at Various Temperatures



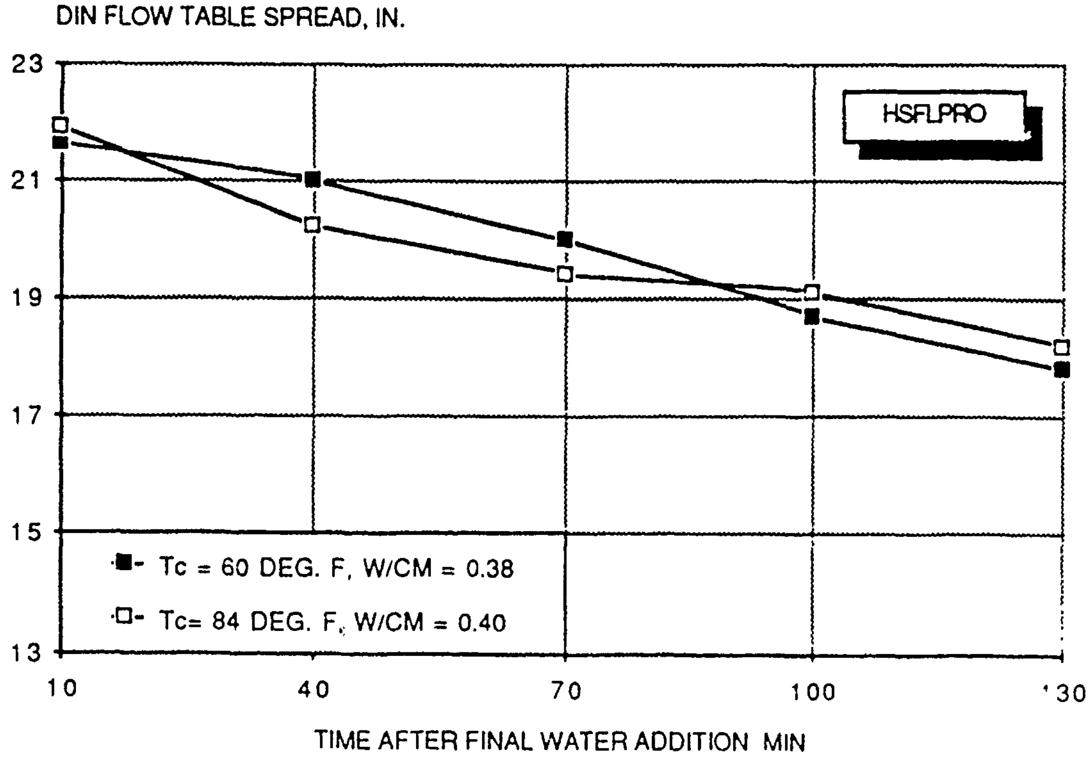


Fig. 5, 6--Slump and Flow Retentions of HSFLPRO Mix at Various Temperatures

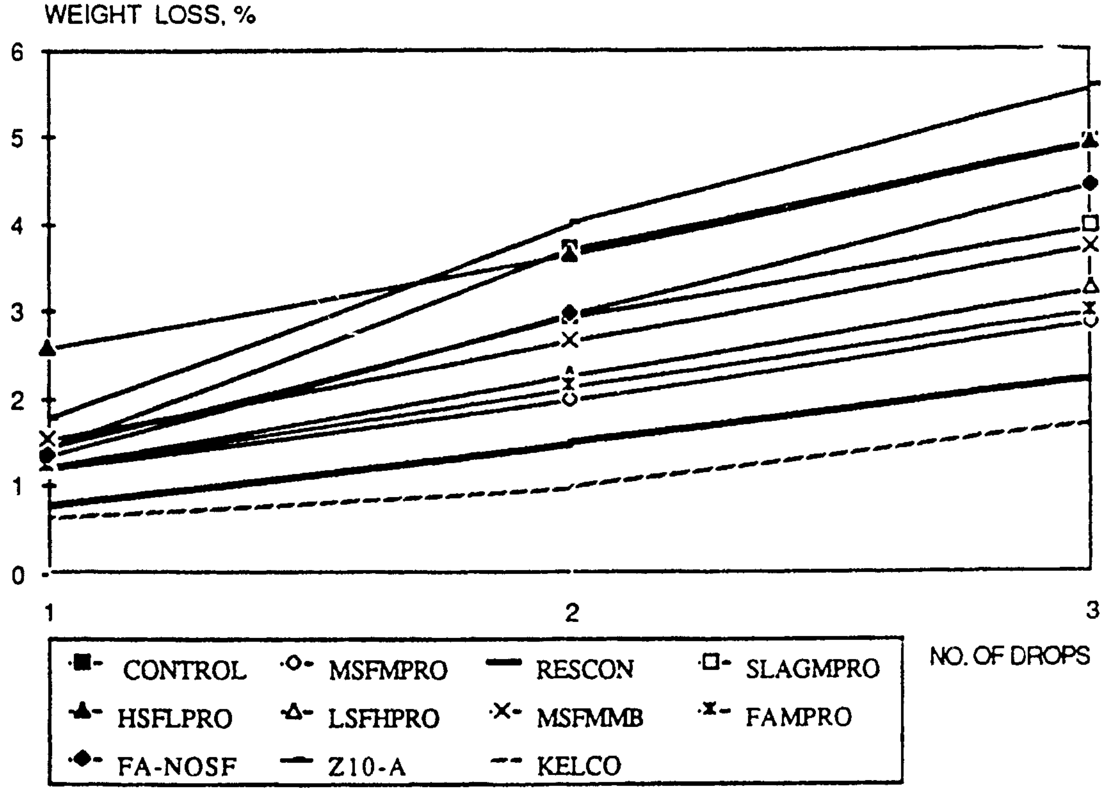


Fig. 7--Average Water Erosion of Fluid Concretes (initial and 30 min)

Based on the results shown in Figure 7, the best washout-resistant concretes appear to be KELCO, RESCON, MSFMPRO and FAMPRO mixtures. These concretes incorporated moderate amounts of AWAs and maintained weight reductions less than 3 percent after three test drops in water. The LSF-HPRO mix, which contained a high concentration of AWA, had a washout weight loss of 3.4 percent after three test drops.

In general, concrete that did not contain any AWA (CONTROL), or concrete that used ineffective AWA (Z10-A), or that which incorporated low dose of AWA (HSFLPRO) exhibited the lowest resistance to water erosion, even though these concretes contained relatively high amounts of silica fume (10 - 13 percent) and low W/CMs (0.36 - 0.38).

Figures 24 - 27 (Appendix C) present the changes in washout values of representative concretes over 2 hours. As shown in Figures 24 and 25 (Appendix C), the water erosion decreased with time for the HSFLPRO and FA-NOSF concretes; a similar behavior was exhibited by the RESCON concrete. The washout resistance of the MSFMMC did not change with time (Figure 26, Appendix C), whereas the washout weight loss of the SLAGMPRO increased over the 2 hr test period. Other evaluated concretes did not show any specific trend and have average washout loss values recorded over 2 hrs similar to those reported in Figure 7.

7.6.3 Underwater Leveling The ability of concrete to spread and self-level under water was evaluated using the underwater leveling test (section 5.1.3). The test consisted of dropping 0.6 ft^3 of concrete in a 36 x 30 in. box through 12 in. of water, then measuring the spread and thickness of the concrete at 6 in. intervals.

Surface profiles are plotted in Figures 28 through 32 (Appendix C). Figures 8 and 9 show surface profiles of the best and worst self-leveling concretes (SLAGMPRO and CONTROL, respectively. The former concrete spread uniformly across the basin and developed a relatively gentle surface slope. On the contrary, the CONTROL concrete did not spread well and resulted in steep surface gradients in all directions. A steep mound at the discharge location was observed for the CONTROL concrete.

Based on the underwater leveling test, concretes capable of flowing well under water and forming relatively flat surfaces are the SLAGMPRO, MSFMPRO, LSFHPRO and FAMPRO mixtures. The underwater leveling test clearly demonstrates the inability of the slump and flow tests to assess the spreadability and self-leveling characteristics of underwater-cast concrete. For example, the CONTROL mixtures, which had the third highest initial flow value, exhibited the poorest underwater spreading and leveling properties (Figure 9).

7.6.4 Bleeding and Separation Bleeding water of freshly-mixed concrete was collected until cessation of bleeding. None of the concretes containing AWAs exhibited any signs of bleeding, despite their high fluidity levels and relatively high W/CMs. The lack of bleeding water is mainly due to the presence of

AWA which increases the retentivity of the free water and prevents it from migrating easily out of the cement paste. Concrete mixtures which did not contain any AWA (CONTROL), or those which did not incorporate an active AWA (Z10-A) showed little bleeding. Their relatively high silica fume contents (13 percent) and low W/CM (0.36) seemed to reduce bleeding.

The propensity of concrete to segregate was evaluated using the segregation test described in section 5.1.4. The weights of fresh concrete, sieved and oven-dried coarse aggregates which were collected from the two disks after dropping a concrete sample over a cone and onto the two disks were determined for seven concretes tested on land and under water. The segregation susceptibility results are summarized in Table 4.

Unlike dry-cast concrete, the majority of underwater-cast concrete flowed onto the outer disk. For example, the concrete spread of underwater- cast concrete (CS_{uw}) for the HSFLPRO mixture was 6363 versus 11.4 for the same value of dry-cast concrete (CS_{dry}). In other words, approximately six times more concrete was collected from the outer plate of the underwater-cast concrete than that of the dry-cast concrete.

The separation of the aggregate from fresh concrete is indicated by the Separation Index (SI). SI values of underwater-cast concrete tested larger than those case above water because of the reduction of cohesiveness caused by water erosion. The additional segregation caused by intermixing with water was evaluated by measuring the spread between the SI_{uw} and SI_{dry} values, or the Separation Resistance (SR). The SI_{uw} and SI_{dry} of the CONTROL mix were 4.3 and 1.9, respectively, and the SR value was 126 percent.

MIXTURE	SLAGMPRO
W/CM	0.43
SLUMP	10.25 IN.
DIN FLOW TABLE	20.6 IN.

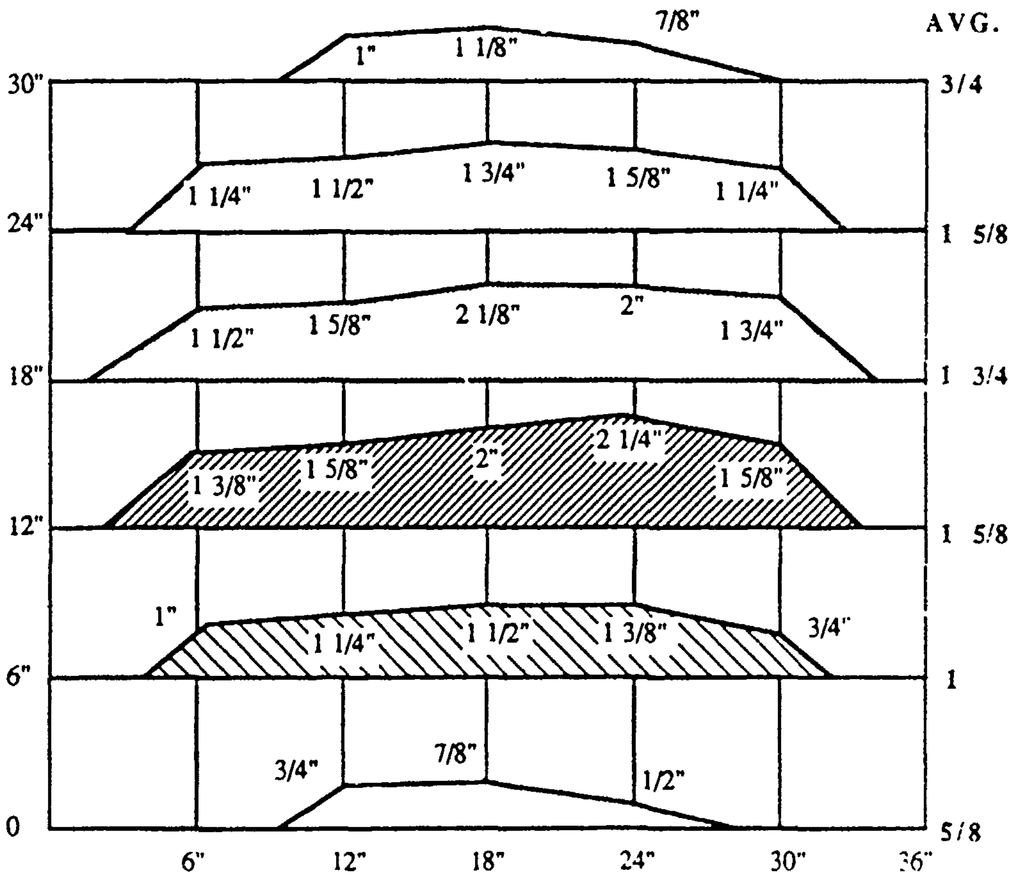


Fig. 8--Underwater Flow of the SLAGMPRO Concrete

MIXTURE	CONTROL
W/CM	0.36
SLUMP	8.5 IN.
DIN FLOW TABLE	21.1 IN.

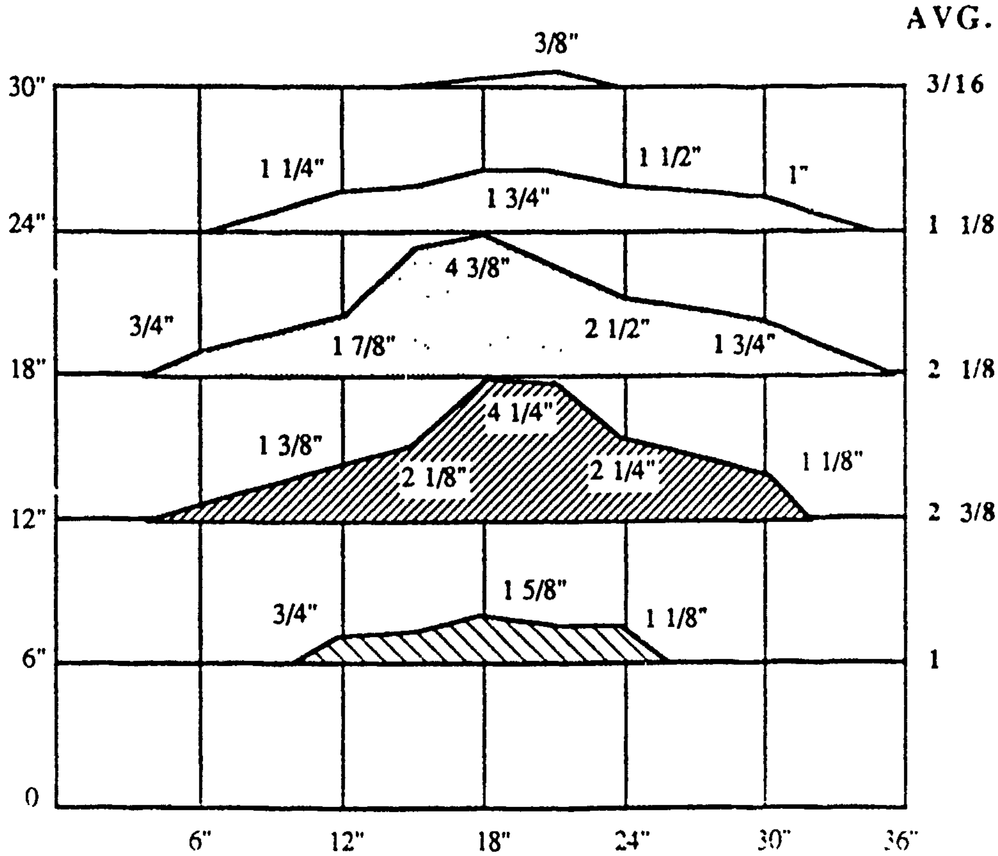


Fig. 9--Underwater Flow of the CONTROL Concrete

Table 4. Summary of the Segregation Susceptibility Test

		CONTROL	HSFLPRP	MSFMPRO	LSFHPRO	MSFMMB	SLAGMPRO	FAMPRO
	Ci	9838	11645	9877	10367	11766	9650	8595
	Co	3393	1500	3393	2765	1602	3382	4113
D	Ai	3296	4257	3778	3603	4213	3572	2929
R	Ao	1253	663	1405	997	636	1316	1492
Y	CS dry	25.6	11.4	25.6	21.1	12.0	26.0	32.4
	AS dry	2.75	13.5	27.1	21.7	13.1	26.9	33.7
	SI dry	1.9	2.1	1.5	.6	1.1	1.0	1.4
	Ci	4223	4413	5455	5575	6472	4250	5665
	Co	7188	7622	7027	6945	5456	8155	8395
U	Ai	1567	1591	1923	1833	2089	1614	1710
W	Ao	3219	3032	2687	2421	1856	3252	3286
	CS uw	63.0	63.3	56.3	55.5	45.7	65.7	64.3
	AS uw	67.3	65.6	58.3	56.9	47.0	66.8	65.8
	SI uw	4.3	2.3	2.0	1.4	1.3	1.1	1.5
	SR	126	9	33	133	18	10	7

$CS = (C_o/C)\ 100$ $\qquad AS = (A_o/A)\ 100$ $\qquad SI = AS - CS$

$$SR = (SI_{uw} - SI_{dry})\ 100/SI_{dry}$$

In general, all the tested concretes were cohesive and homogeneous. They did not exhibit excessive amounts of separation, even when they were dropped through water. Concretes with the lowest SR factors were the FAMPRO, HSFLPRO, SLAGMPRO, MSFMMB and MSFMPRO mixtures. On the other hand, the LSFHPRO and CONTROL concretes suffered greater additional segregation than other mixtures when placed in water.

7.6.5 Setting Time Table 5 summarizes the setting times of concretes prepared and tested at approximately 55°, 65° and 85°F which were measured to evaluate the stiffening rates at various service temperatures. The HSFLPRO, Z10-A and CONTROL mixtures exhibited long delays in setting. These concretes had little or no AWAs but incorporated retarding WRAs to mitigate sharp fluidity losses.

The addition of $CaCl_2$ to any of these concretes accelerated the setting but also resulted in sharper reductions in fluidity.

The SLAGMPRO mix had an initial setting time of 72 hr at 67°F which was reduced to 11 hr after adding $CaCl_2$ as 0.5 percent of the weight of cementitious materials. However, the use of $CaCl_2$ caused a decrease in fluidity retention, therefore, a balance between fluidity and setting time had to be achieved. The MSFMPRO, FAMPRO, LSFHPRO and KELCO concretes did not incorporate any $CaCl_2$ and exhibited initial setting times ranging between 13 and 27 hours.

Elevated concrete temperatures resulted in moderate increase in stiffening, especially when $CaCl_2$ was used. Apart from the initial delay in stiffening, the difference between the initial and final setting times seemed to be practically unchanged (1 to 2 hrs) regardless of the temperature. Thus the effect on strength development at early ages should not be affected.

In general, extended set retardation can increase the bleeding and segregation of the concrete and result in a non-homogeneous matrix. However, none of these concretes exhibited any bleeding. Therefore, extended setting times of 10 to 15 hrs can be considered as prolonged working periods for handling and placing the concrete under water. Such setting times can be acceptable so long as the concrete is protected from flowing water to prevent water erosion. If the setting time is delayed for a long period of time, a shelter should be installed to protect the fresh concrete from water movements or $CaCl_2$ should be incorporated to accelerate the stiffening of the concrete.

As presented in section 7.3.6, non-chloride set accelerators were examined and proved to have marginal benefits when high concentrations of HRWRAs and AWAs are employed. The addition of $CaCl_2$ is believed to pose a small added risk of steel corrosion since the oxygen concentration under water is low. Whenever $CaCl_2$ is added to the concrete mix, or when concrete is placed in sea water, special consideration should be given to the quality of selected aggregates. For example, the use of alkali reactive aggregates which can impair the durability of the concrete should be avoided.

Table 5. Summary of Setting Times of Final Mixtures at Various Temperatures

	SETTING TIME, HOURS					
CONCRETE TEMP. (F)	50 - 55		65 - 70		85 - 90	
MIX -- CACL2 (% CM)	INITIAL	FINAL	INITIAL	FINAL	INITIAL	FINAL
CONTROL -- 0	31	32.5	26.5	28	25	26.75
HSFLPRO -- 0	34	36	30	32.25	29	30.5
MSFMPRO -- 0	18	20	13	14.5	10.5	12
LSFHPRO -- 0	22	25.5	15.5	17	12	13.5
MSFMMB -- 1.25	8	9.75	- -	- -	5.5	7.25
SLAGMPRO -- 0.5	14	15	11	12	9	10
FAMPRO -- 0	21.5	23	13.5	15.25	12.25	14.25
FA-NOSF -- 0.75	18	19.5	16.5	18	13	14.5
RESCON -- 0.5	21.5	23	17.5	19	11.5	13
KELCO -- 0	- -	- -	17	19.25	- -	- -
Z10-A -- 0	- -	- -	58	60	48	50

7.6.6 Compressive, Splitting Tensile an Flexural Strengths Table 6 presents the strength results of the 11 concrete mixtures along with their W/CMs and measured air volumes. The concrete specimens were cast and fully compacted on land. All concrete mixtures developed good strength values at early and late ages. The rankings of concretes according to their compressive, splitting tensile and flexural strengths are listed in Tables 9, 10 and 11, respectively (Appendix C).

Concretes with low W/CMs and high concentrations of silica fume, such as the CONTROL, HSFLPRO and Z10-A mixtures, exhibited higher strength values than the other concretes. On the other hand, concretes that had relatively low cement contents or high W/CMs, such as LSFHPRO, SLAGMPRO, FAMPRO and KELCO mixtures, developed lower strength values. The FA-NOSF mix had more fly ash than most concretes and did not contain any silica fume. Its strength was considerably less than other mixtures that had higher W/CMs or less cement contents.

Table 6. Strength Results

			STRENGTH, PSI						
			COMPRESSIVE			SPLIT. TENSILE			M. R.
MIXTURE	W/CM	% AIR	7 D.	28 D.	56 D.	7 D.	28 D.	56 D.	56 D.
CONTROL	0.36	3.25	6270	10525	11585	690	920	1000	1180
HSFLPRO	0.38	4	6350	10085	11240	665	870	955	1105
MSFMPRO	0.42	4.25	5740	7910	9510	615	695	835	1080
LSFHPRO	0.46	3.5	4765	6850	8065	535	675	740	880
MSFMMB	0.45	3.5	5485	8225	9035	595	770	820	910
SLAGMPRO	0.43	4.75	3780	8240	8630	485	890	860	1030
FAMPRO	0.42	4.5	4730	7720	7635	595	790	825	850
FA-NOSF	0.41	3	5240	6915	7930	455	535	560	- -
RESCON	0.44	2.5	4990	5610	8370	515	655	820	- -
KELCO	0.46	3	3675	6920	7905	355	570	620	750
Z10-A	0.36	2.5	5610	10685	10740	560	855	865	- -

7.6.7 Abrasion Resistance The wear resistance of concrete cast and fully compacted in the dry was compared to the wear resistance of concrete cast under water This was carried out to evaluate the additional wear damage that may result because of the intermixing of concrete with water and the lack of consolidation. Underwater-cast specimens were prepared by dropping fresh concrete 12 in. through water without consolidation, as described in section 5.2.1. The average 56 day cumulative abrasion weight losses are presented in Table 7. The final spreads in weight reductions between underwater- cast and dry-cast specimens are also listed. Figures 33 and 34 (Appendix C) plot the weight losses of concretes cast above and under water, respectively. The 72 hr cumulative abrasion weight losses of concretes cast above water ranged between 2.5 and 4.9 percent. All dry-cast concretes, except the FAMPRO and LSFHPRO mixtures, experienced weight reductions less than 3.5 percent after 72 hrs of testing. When cast on land, the highest wear-resistant concretes were those made with low W/CMs, such as CONTROL and HSFLPRO mixtures, as well as the FA-NOSF concrete which incorporated a relatively high cement content.

However, when cast in water, the CONTROL and HSFLPRO concretes suffered approximately 6 percent weight reductions after 72 hrs of testing. These values were 114 and 144 percent,

respectively, greater than those obtained with dry-cast specimens. The large spread in wear damage was due to the relatively low washout resistance levels of these two concretes and their poor underwater spreading characteristics. For example, the CONTROL and HSFLPRO concretes showed the lowest resistance to water erosion (4.9 percent), and the CONTROL mix had poor self-leveling properties (Figure 9).

When concrete was cast in water, the highest abrasion-resistant concrete were those which had good wear-resistant values when cast above water and also possessed superior washout resistance values and good underwater spreadability levels. Examples of these concretes are the RESCON, FANOSF and MSFMPRO mixtures. The cumulative weight reductions after 72 hrs of testing were limited to 5 percent when cast under water. These three mixtures had 17, 52 and 46 percent more abrasion weight losses when cast under water than when cast above water. Other concretes, such as the LSFHPRO mix, which had a good washout resistance exhibited a low spread in wear damage between the results obtained from underwater-cast and dry-cast specimens (23 percent). However, due to its low silica fume content (4 percent) and high W/CM (0.46), its initial abrasion resistance was relatively low (4.9 percent) when cast above water.

7.6.8 Bond Strength The bond development between concrete and reinforcing steel was evaluated for one of the best performing concretes which incorporated an AWA (MSFMPRO) and also for the CONTROL mixture which did not use any AWA. This was carried out to determine the effect of AWA and sound mix proportioning on preserving the integrity of the concrete when placed in water.

The pullout bond stresses between the vertical steel bar and hardened concrete were measured for concrete specimens cast and fully compacted above water versus others that were cast under water. The latter was prepared by dropping concrete through 12 in. of water without consolidation (section 5.2.3). The reinforcing steel consisted of No. 6, Grade 40, deformed bars. Four specimens were cast for each concrete mixture, a total of 16 molds were prepared. The specimens were cured for 28 days

then tested for pullout strength. The slip between the steel and concrete versus the pullout load were recorded. The test was terminated when the concrete failed in tension or the steel started to yield.

Figures 10 and 11 show the measured bond stresses versus bar slip values for the CONTROL and MSFMPRO concretes, respectively. Results of two representative specimens from each concrete are plotted. Except for the underwater- cast CONTROL concrete, the loading of the tested specimens were discontinued due to the yielding of the steel bars. The underwater-cast CONTROL concrete was the only concrete to fail due to the splitting of the concrete before steel yielding (Figure 11).

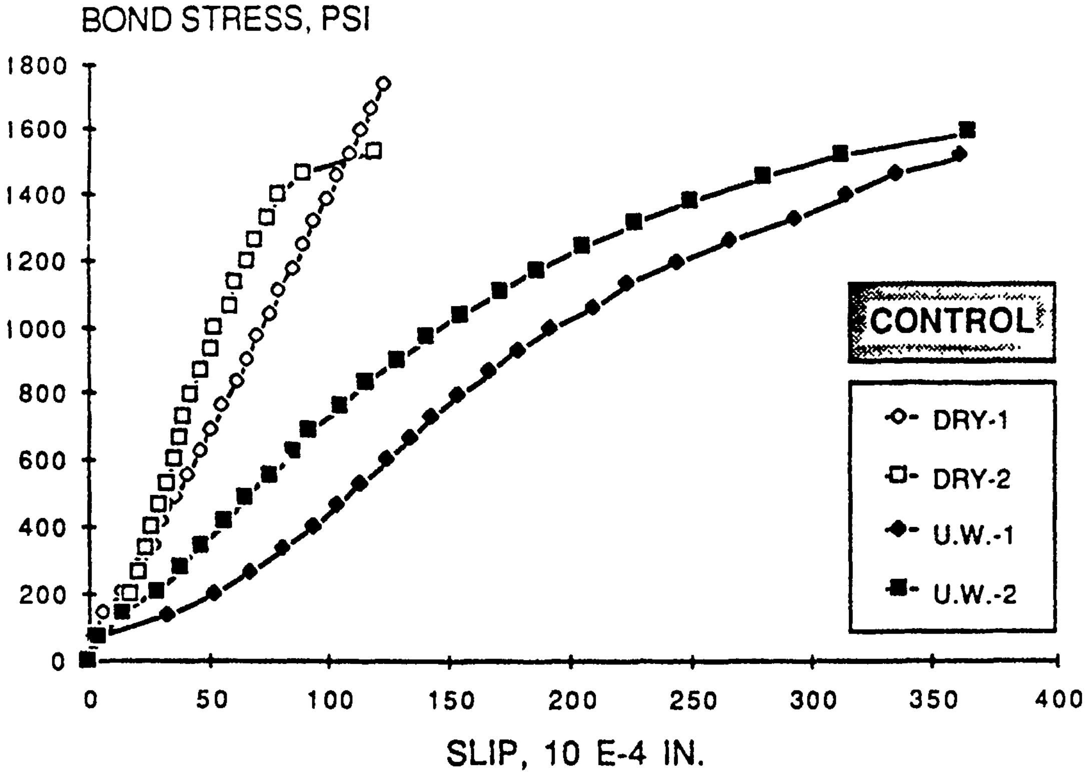
The average bond stress of the dry-cast CONTROL mixture at 0.01 in. slip was approximately 1,500 psi, whereas the average bond stress for the underwater-cast concrete was approximately 600 psi. On the other hand, the average bond strength at 0.075 in. slip of the underwater-cast MSFMPRO mix was approximately 75 percent of the value secured with dry-cast concrete. This 75 percent value compares only to 30 percent residual bond strength for the CONTROL concrete at that slip value.

<u>7.6.9 Temperature Developments</u> Concrete was placed in a 4 × 8 in. mold with a thermocouple at its center. The mold was well insulated to reduce temperature losses. Temperature developments were monitored for 6 days. Figures 12 - 14 show the temperature history for 10 tested concretes. All concretes, except the SLAGMPRO mix, which had lower cement content than others, had similar temperature developments. Maximum recorded temperature values were 98° ± 5°F. The SLAGMPRO mixture had the lowest peak temperature (93°F), while the LSFHPRO, MSFMMB, FA-NOSF and RESCON concretes had the highest peak values (103°F). Sharp rises in temperatures were delayed for 5 to 15 hrs for most concretes, except the Z10-A mixture which was delayed for 40 hours. Peak temperatures were reached shortly after the final setting time. The high temperatures developed by these mixtures would preclude their use in massive placements but should not create severe temperature gradients in thin placements.

Table 7. Summary of Abrasion-erosion Results

	% CUMULATIVE ABRASION WT. LOSS					
	CAST ON LAND					
TESTING HRS.	12	24	36	48	60	72
CONTROL	0.4	0.8	1.3	1.7	2.3	2.8
HSFLPRO	0.2	0.6	1	1.4	1.9	2.5
MSFMPRO	0.2	0.5	1	1.7	2.4	3.3
LSFHPRO	0.5	1.3	2.3	3.3	4.1	4.9
MSFMMB	0.4	0.8	1.3	1.7	2.4	2.9
SLAGMPRO	0.3	0.9	1.3	1.9	2.6	3.4
FAMPRO	0.2	0.8	1.5	2.4	3.3	4.2
FA-NOSF	0.2	0.6	1.2	1.9	2.4	2.9
RESCON	0.5	1.1	1.8	2.4	2.9	3.3

	% CUMULATIVE ABRASION WT. LOSS						
	CAST UNDER WATER						% SPREAD
TESTING HRS.	12	24	36	48	60	72	@ 72
CONTROL	1.6	3.1	3.8	4.4	5.2	6	114
HSFLPRO	1.6	2.8	3.6	4.4	5.2	6.1	144
MSFMPRO	0.5	1.1	1.8	2.8	3.7	4.8	45
LSFHPRO	0.7	1.6	2.7	3.6	5	6.4	31
MSFMMB	0.4	1	2.1	3.6	4.5	5.3	83
SLAGMPRO	0.5	1.2	2.2	3.1	4.1	5.2	53
FAMPRO	0.5	2.1	3.4	4.5	6.1	7.6	81
FA-NOSF	0.6	1	2	2.9	3.7	4.5	55
RESCON	0.5	1.2	1.9	2.7	3.4	3.9	18



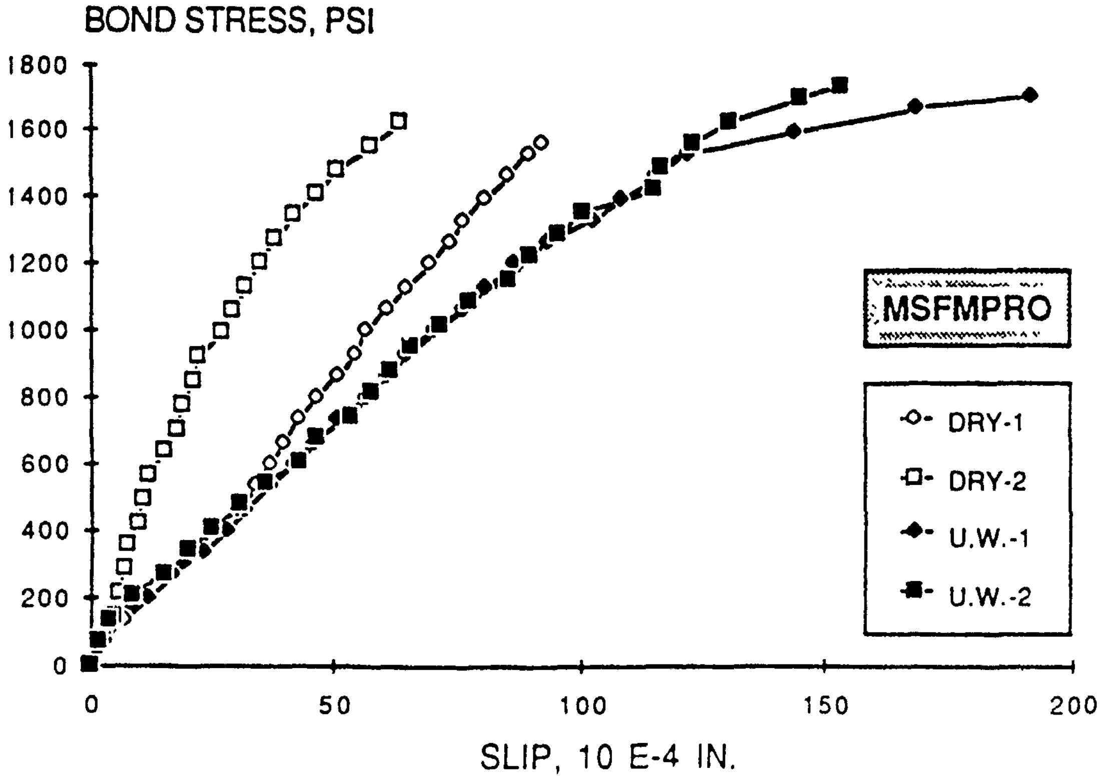
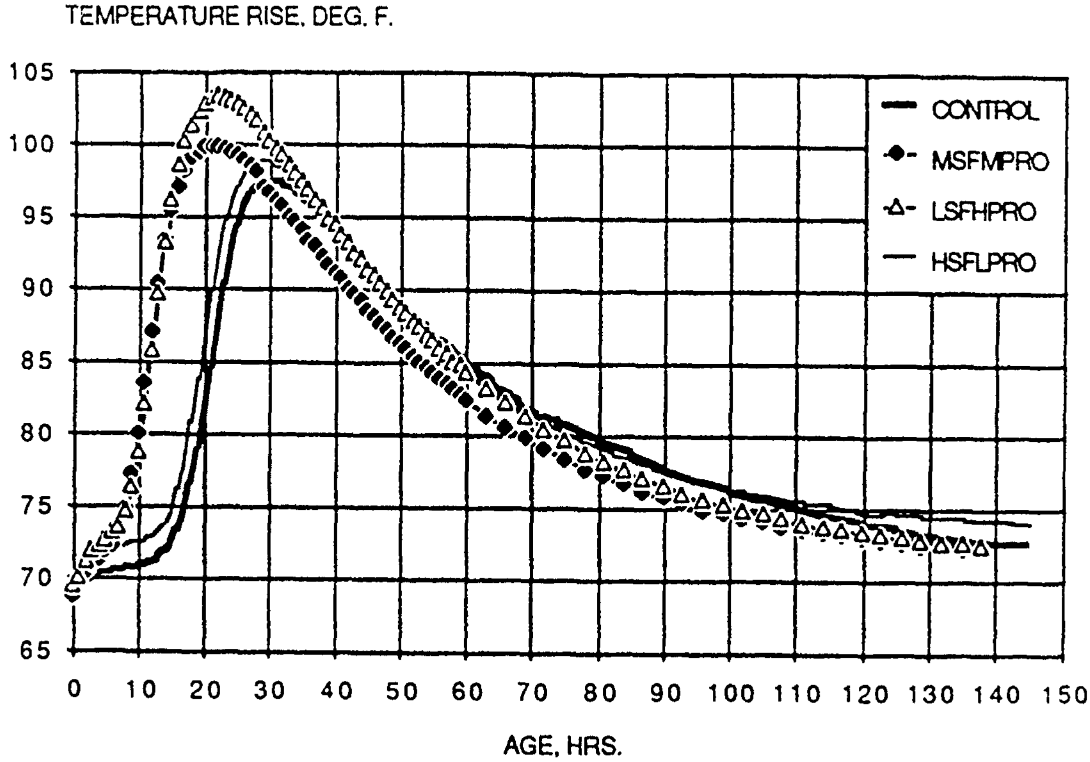


Fig. 10, 11--Bond Strength of CONTROL and MSFMPRO Concretes



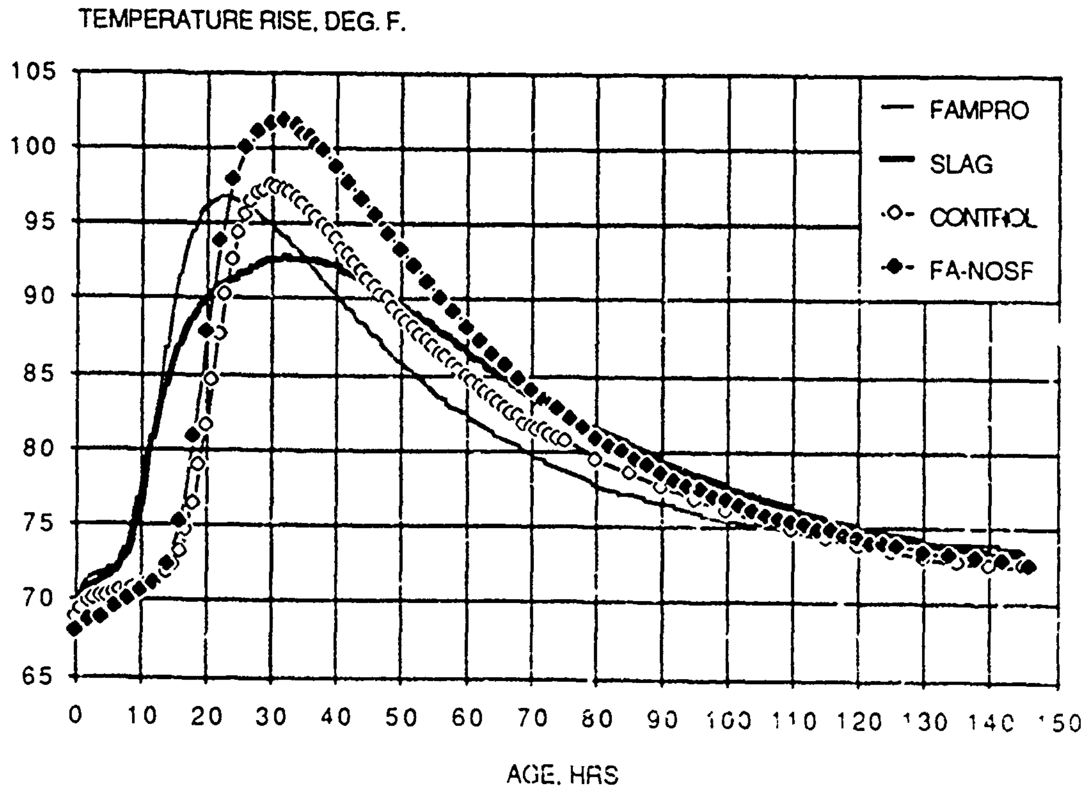


Fig. 12, 13--Temperature Developments

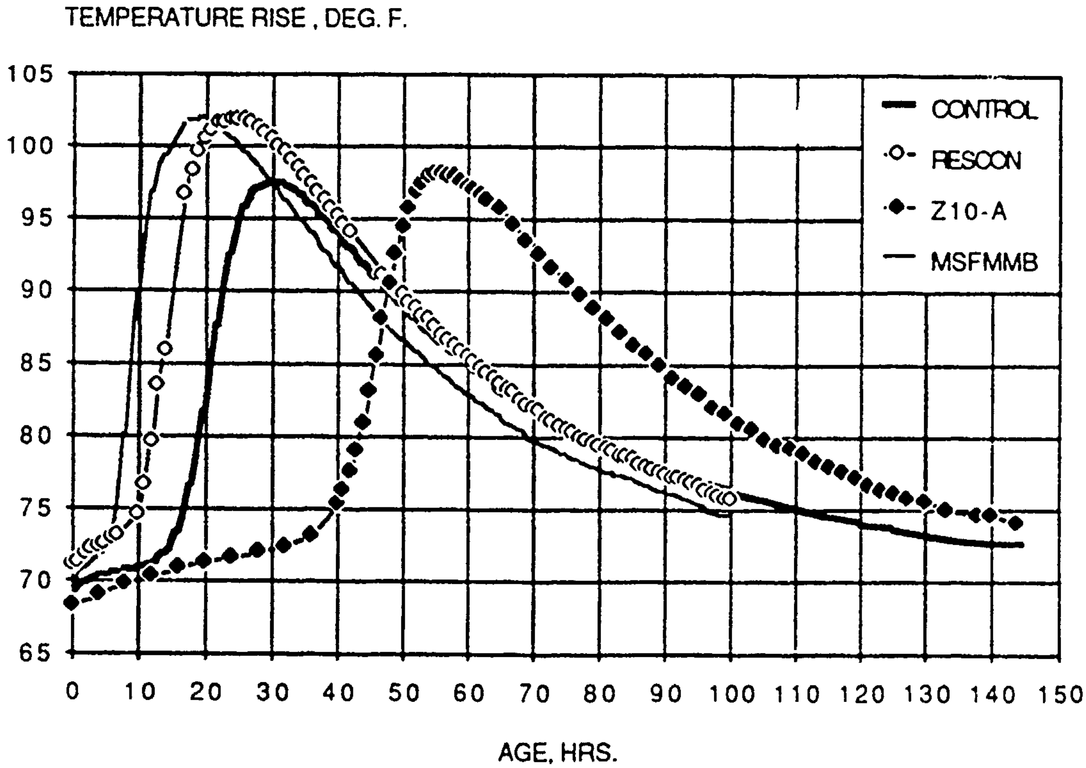


Fig. 14--Temperature Developments

7.7 Effect of AWA's and HRWRA's on Setting Time

A series of experiments was conducted to determine the influence of incorporating AWAs and HRWRAs on concrete stiffening. The stiffening rates of four representative final mixtures incorporating AWAs supplied by Master Builders, Protex, Rescon and Kelco were evaluated. These concretes were MSFMMB, MSFMPRO, RESCON and KELCO, respectively.

The stiffening rates were monitored for concrete mixtures prepared without any AWA (-AWA) in order to evaluate the effect of the HRWRA on setting. Similarly, the HRWRA was omitted from the mix (-HRWRA) to assess the delay of setting caused by the AWA. Finally, the combined effect of both AWA and HRWRA on the setting was determined by preparing concrete with neither additive (-All).

These three types of concretes were compared to the original control mixtures which contained both AWAs and HRWRAs. The $CaCl_2$ employed in the MSFMMB and RESCON mixtures was incorporated into the other six concretes related to these two control concretes. The Sikament 85 HRWRA employed for this exercise was from a different batch than that used for the initial development of the concrete mixtures.

Fresh concrete was dry-sieved with a No. 4 sieve to retain the mortar. This mortar was then used to cast two standard containers which were stored in a fog room at approximately 73 ± 3°F. The stiffening rate of the mortar was monitored frequently using the Proctor Penetration test (ASTM-C 403). The initial and final setting times were considered to occur when the penetration resistance of the concrete was 500 and 4,000 psi, respectively.

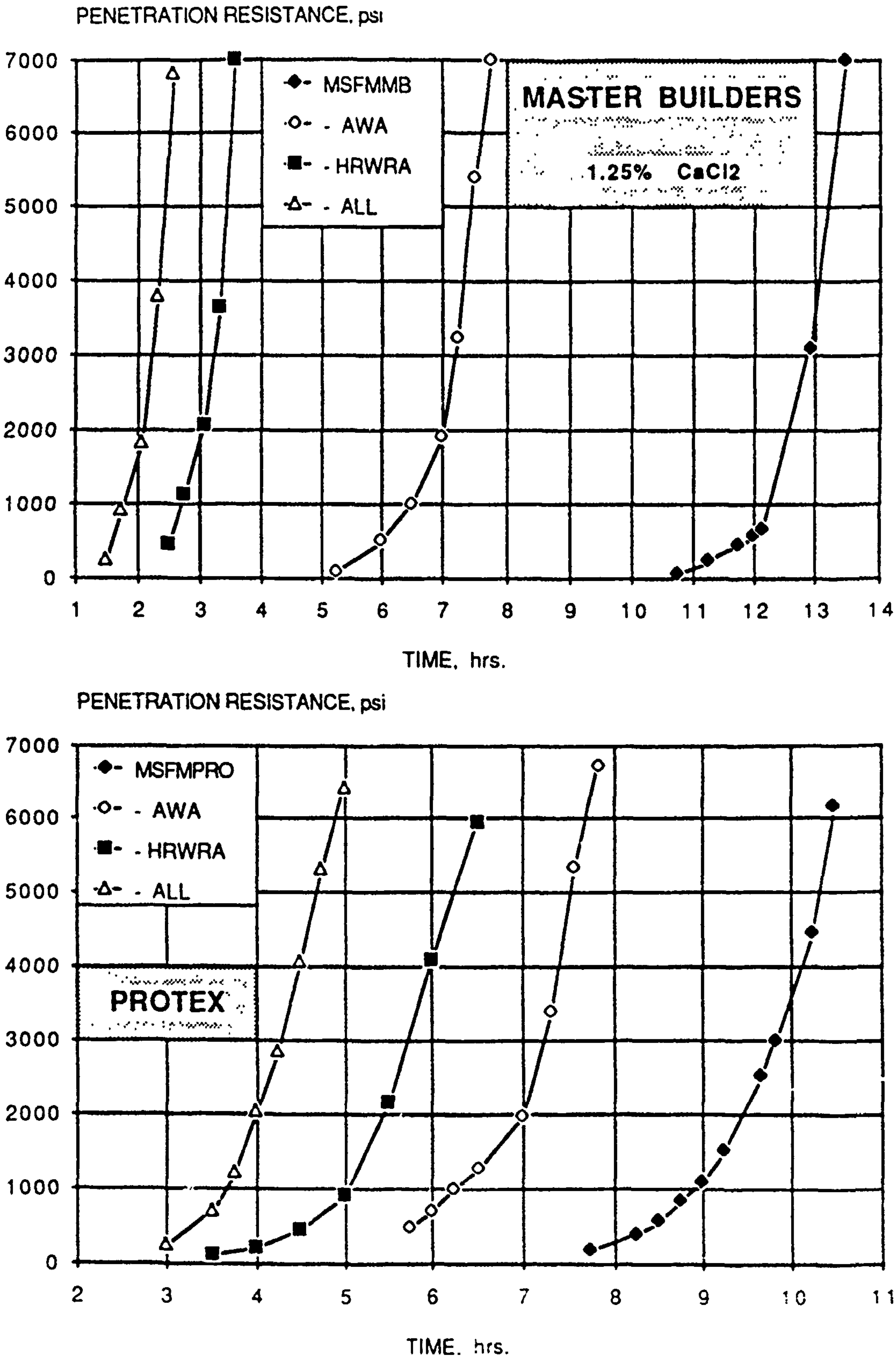
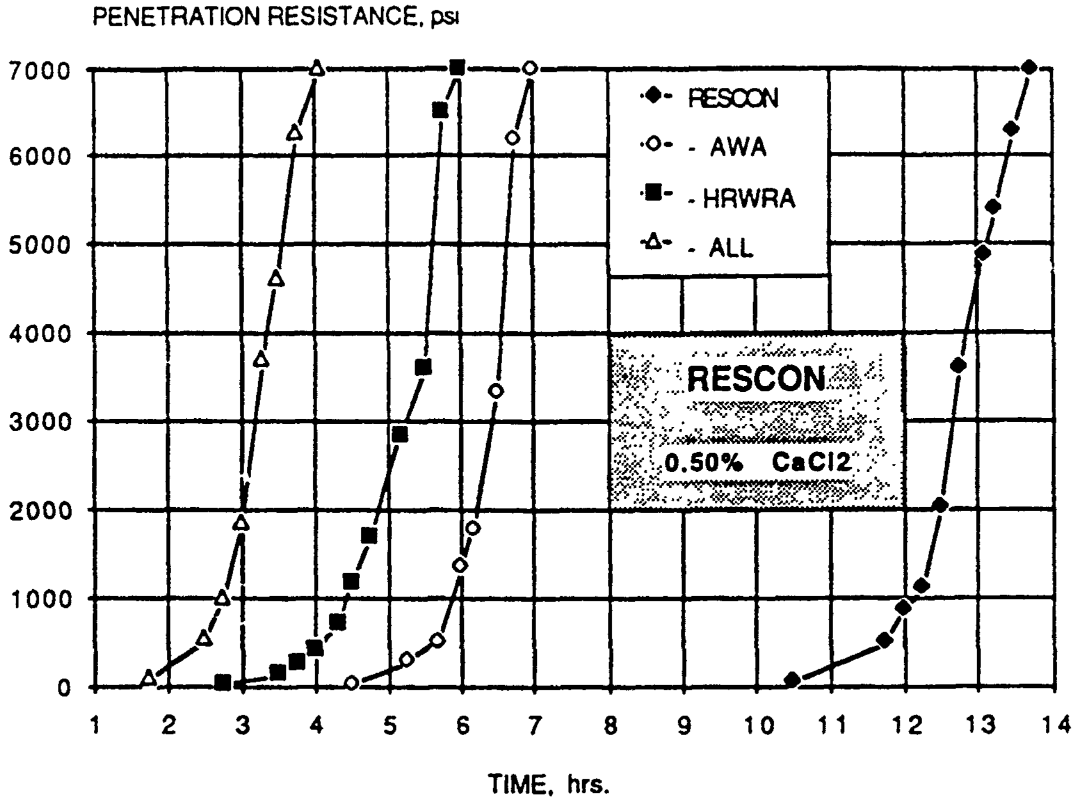


Fig. 15, 16--Hardening of Mixtures Containing Master Builders and Protex AWAs



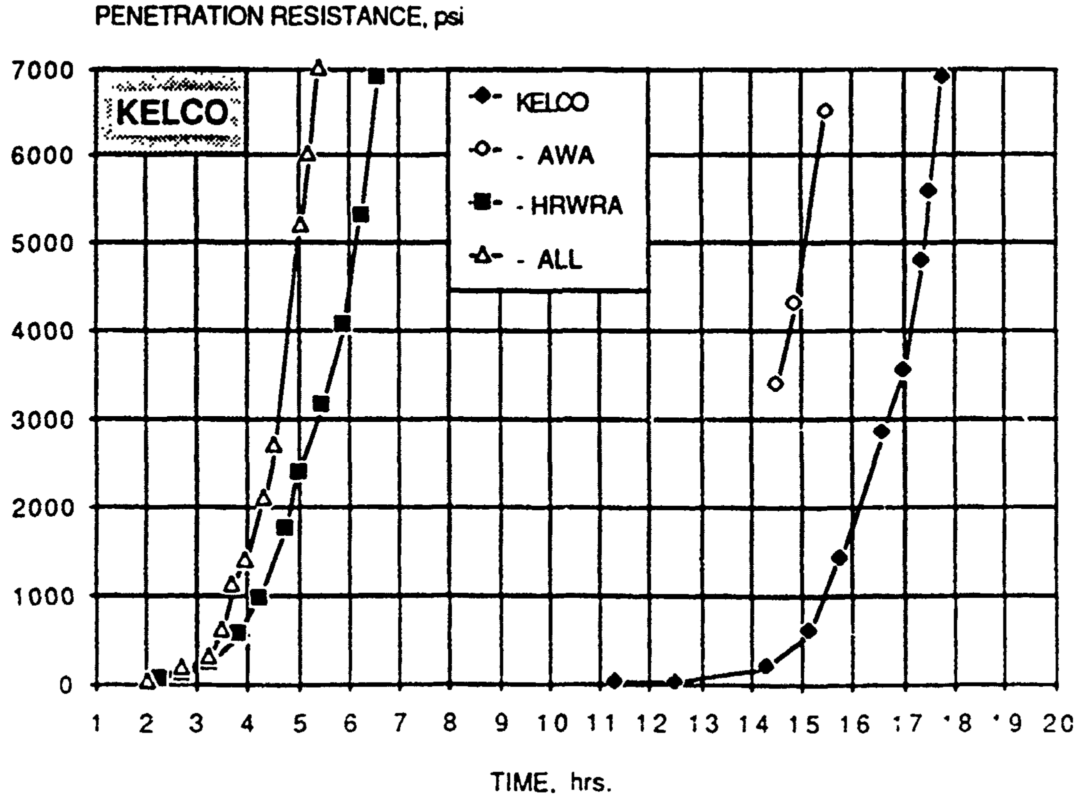


Fig. 17, 18--Hardening of Mixtures Containing Rescon and Kelco AWAs

The rate of stiffening of the 16 concrete mixtures are plotted in Figures 17 - 20. These figures suggest that the high concentration of HRWRAs required with concretes containing AWAs was mostly responsible for the long delays in stiffening (-AWA mixtures). This was especially true with the KELCO mix which incorporated a large dose of HRWRA. The contribution of AWAs to the delay in stiffening was smaller than that of the HRWRA (-HRWRA mixtures). In general, all AWAs caused 1 to 2 hr delays in stiffening over concretes made without AWAs on HRWRAs (-All).

The set retardation of concrete containing both HRWRA and AWA was higher than the combined delay used by each individual additive. This was especially true for the MSFMMB and RESCON concretes which contained $CaCl_2$. However, once the cement paste started to stiffen, the hardening rate of all concrete mixtures proceeded at similar rates regardless of the additive(s) in use.

7.8 Summary and Conclusions

The need to place fresh concrete under water in thin lifts for repairing small and relatively shallow scour holes poses several challenges. Fluid concrete suitable for such repairs should flow readily under water with minimum segregation and should self-compact and self-level. Furthermore, such concrete should possess high resistance to water dilution and should remain workable throughout the placement operation, but it should set quickly thereafter. The hardened concrete must adhere to damaged surfaces and reinforcing steel and develop high wear resistance to waterborne debris.

An exhaustive study was undertaken to optimize mix proportionings and qualify different materials and additives. A total of 54 trial mixtures were batched and tested. Eleven concretes which incorporated various types and combinations of admixtures were selected, and several important properties which are needed to secure durable repair surfaces were evaluated.

All concretes had high initial slump and flow values. The combined use of the HRWRA and AWA caused long retardation in stiffening which resulted in good fluidity retention. The maximum slump loss of most concretes at 65°F was limited to 10 - 40 percent 2 hrs after the end of mixing. Similarly, the flow values showed maximum drops of 5 to 30 percent after 2 hours. Concrete mixtures that contained little or no AWA experienced sharper reductions in slump values than those employing medium or high concentrations of AWA. The rate of decrease in slump and flow values at 85°F were similar to those experienced at 65°F. A slightly higher water content was needed for some concretes to secure comparable initial fluidity levels. This was especially true for concrete containing little or on AWA.

Concretes incorporating medium or high doses of AWAs exhibited good resistance to water erosion and flowed well under water. Such concretes developed flatter surface slopes than concrete containing little or no AWA. The addition of an AWA enhances the plasticity and extends the workable time of concrete. Similarly, it can eliminate bleeding, reduce segregation and increase the resistance to water erosion. As a result, homogeneous and high quality concrete can be secured under water.

The abrasion weight loss after 72 hrs of testing ranged between 2.5 and 4.9 percent for concrete cast in the dry. The abrasion resistance was enhanced as the W/CM decreased. Additional abrasion weight reductions ranging between 18 and 144 percent resulted when the concrete was cast loosely in water. Concretes having high washout resistance values and good underwater spreadability levels suffered the least additional wear damage when cast under water.

Based on the observations presented in this chapter, the following recommendations are given for proportioning fluid concretes suitable for repairing small and relatively shallow scour holes under water.

A. A number of standard and non-standard laboratory tests must be employed to select admixtures and qualify concretes for repairing damaged surfaces under water. Several rheological and mechanical properties should be evaluated to ensure proper placability and increase the probability of success and cost effectiveness of subsequent field placements.

B. The cementitious materials of such concrete should consist of 600 lb/yd^3 of cement and 40 lb/yd^3 of silica fume. A 30 lb/yd^3 fly ash may be added to improve the workability of this concrete.

C. The lowest possible W/CM (0.40 to 0.42) should be used in order to enhance abrasion resistance. A HRWRA should be added to reduce the water demand needed to fluidize the concrete.

D. Hard natural pea gravel should be secured to improve the wear resistance of the concrete. The sand content should be approximately 45 ± 2 percent of the total aggregate volume to enhance the workability and cohesiveness of the fresh concrete.

E. Among the evaluated AWAs that proved to be effective are those supplied by Kelco, Master Builders, Protex and Rescon. The incorporation of high doses of AWAs and HRWRAs can lead to long delays in initial setting (in excess of 15 hours). AWAs used in low doses with low strength concretes may improve the f'_c. However, high concentrations of AWAs appear to reduce the f'_c of concretes with medium and low W/CMs. The addition of an AWA to concrete in a pre-hydrated form may result in higher f'_c values than concrete containing dry-blended AWA.

F. De-airing admixtures should be used to reduce the entrapped air caused by some AWAs. A $CaCl_2$ accelerator may be incorporated to reduce excessive delays in stiffening.

G. The washout weight loss should be limited to 3 percent after three test drops in water. The abrasion weight reduction of dry-cast and underwater-cast concretes should not exceed 3.5 and 5 percent, respectively.

H. Based on the findings reported in this chapter, concretes similar to the MSFMPRO, KELCO, RESCON, SLAGMPRO and FA NOSF mixtures can be suitable for repairing small and relatively shallow scour holes under water.

CHAPTER EIGHT

CONCRETES AND PLACEMENT METHODS FOR REPAIRING SMALL AND RELATIVELY SHALLOW HOLES

8.0 Purpose

In repairing relatively shallow scour holes (1 to 3 ft in depth) under water, the limited depth of these holes and the frequent movements of the placement device through water to repair neighboring areas makes it difficult to maintain a continuous end seal, as normally done in massive tremie placements. Therefore, concrete may have to be dropped a short distance in water and should be designed to resist segregation and water erosion.

This chapter summarizes the results of nine laboratory placements that aimed at evaluating fluid concretes and identifying compatible casting techniques suitable for repairing small and relatively shallow scour holes under water. Five mixtures were cast under water using a vertical tremie pipe to compare their suitabilities for repairing shallow scour holes. Three concretes were then cast in water using a 45^0 inclined pipe to compare the proposed inclined tremie method to the conventional vertical one. A promising concrete mixture was also cast above water using the inclined tremie technique to evaluate the additional damage caused by underwater casting when a high quality concrete is used.

The concrete was cast in a placement box which bottom was formed in a step-type configuration to simulate a small scour hole. Several properties necessary to ensure successful repairs were evaluated. The following areas were of particular interest:

A. To investigate the spreadability of promising repair concretes and compare the results to those obtained with the underwater leveling test (section 7.6.3).

B. To compare the flowability of concrete around obstacles and into neighboring areas without suffering much losses in mechanical properties.

C. To evaluate the bond strength between dry-cast and underwater-cast concretes and between two consecutive lifts.

D. To compare the capability of the vertical tremie method to the proposed inclined tremie technique in reducing water erosion and segregation.

A large scale field experiment was also carried out to examine the performance of a promising repair concrete under field conditions and establish guidance for acceptable spacings between discharge locations. An approximate 16 x 2.5 x 2.5 ft hole submerged in 3.5 ft of water was filled with a promising concrete mixture using an inclined tremie pipe. The resultant surface appearance and in-place density and strength were determined.

8.1 Laboratory Investigation

Five of the 11 final concretes evaluated in Chapter Seven were selected for this study. These concrete were the MSFMPRO, FAMPRO, SLAGMPRO, HSFLPRO and CONTROL mixtures. The first three had similar mix proportions, except for their contents of fly ash and blast furnace slag. The HSFLPRO mixture had a low W/CM and incorporated a small dose of AWA and a high concentration of silica fume. The CONTROL concrete did not incorporate any AWA but contained a high silica fume content.

<u>8.1.1 Placement Box and Base Slab</u> A steel basin which was lined with plywood was used for the placement box. Its interior dimensions were 6 x 2.5 x 2.25 ft (Figure 19), and its bottom was formed in a step-type configuration in order to investigate the ability of the cast concrete to spread over and past the steps. The bottom of the placement box was covered with a base slab measuring 18 in. wide and 5 in. in thickness (Figure 35, Appendix D). The base concrete ("old") was cast above water and was centered across the width of the box.

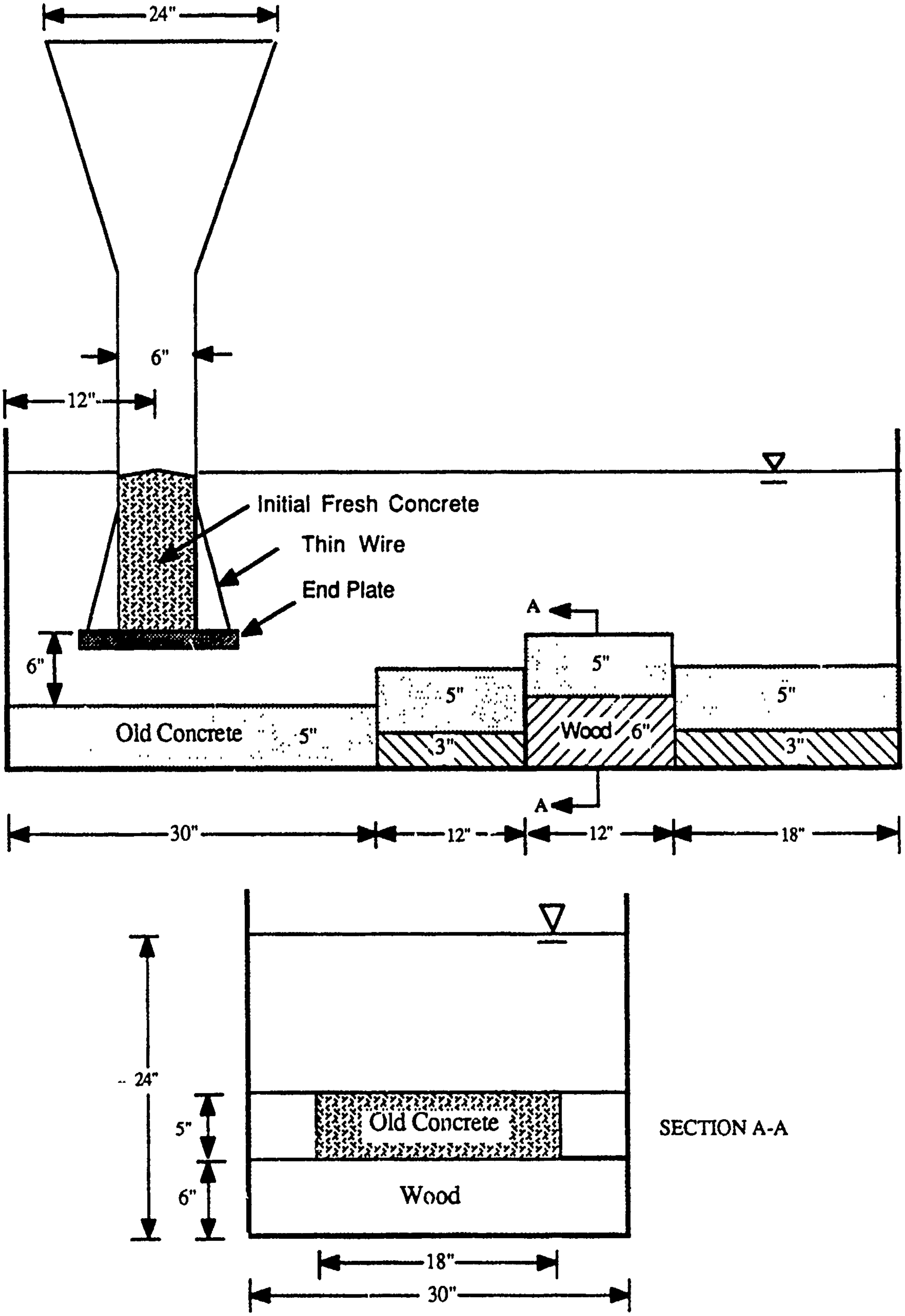


Fig. 19--Schematic of the Placement Box

The "old" concrete contained approximately 580 lb/yd^3 of cement and had an average W/CM of 0.43. Its fluidity was kept low to avoid bleeding. The air content and unit weight of the "old" concrete were measured, then 3 x 6 in. cylinders were cast to test control density and f'_c values. After casting the base slab, the concrete was covered with wet burlap for one day. Its upper surface was then roughened with a wire brush until the top aggregates were exposed in order to enhance its bonding to subsequently-cast concrete ("new"), as shown in Figure 36 (Appendix D). The basin was then cleaned and sealed. The box was filled with 2 ft of water for the eight underwater placements.

<u>8.1.2 Casting Concrete</u> The "new" concrete was cast in two 7 ft^3 lifts. Each batch was mixed separately following the charging procedure described in section 7.2. A mineral oxide pigment was added to the first mix (Mix A) to differentiate it from the second batch (Mix B). Each batch was sampled prior to casting and tested for flow, slump, unit weight and air content. Four 3 x 6 in. cylinders were then cast and consolidated above water to determine the control density, f'_c and splitting strength values.

Concrete was transferred to a bottom-dumping bucket which was then mounted over the tremie pipe. After casting the initial lift, the second batch was mixed, loaded into the bucket and cast in the basin. No attempt was made to remove any sediments before casting the top lift since the ability of concrete to bond to underlying freshly-cast concrete was of interest. The time lag between the two placements was approximately one hour.

<u>8.1.3 Tremie Operations</u> Five concretes were cast under water using a vertically suspended tremie pipe measuring 6 in. in diameter. A hopper was fabricated and bolted to the top of the pipe to facilitate the transferring of concrete into the placement device. The bottom of the pipe was sealed with a rubber-lined wooden plate which was secured to the pipe by steel wires (Figure 37, Appendix D).

The pipe and hopper were first lubricated with water, then partially filled with concrete before submerging the bottom of the pipe in water. The pipe was positioned one foot from the front side of the box (Figure 38, Appendix D). Its bottom was held 6 in. over the base slab to reduce the initial free-fall of concrete through water. The pipe and hopper were then filled with concrete before cutting the wire to remove the end plate. The discharge of concrete was continuous while the pipe was fixed in position. At the end of placement, the pipe was retrieved, cleaned and sealed. To cast the second lift (Lift B), the end of the pipe was again positioned one foot from the front side of the box and 2 to 6 in. over the surface of the first lift (Lift A).

8.1.4 Inclined Tremie Operations Three slabs were cast under water and one above water using the above tremie pipe that was inclined at 45^0. The pipe was tilted to decrease the velocity of the concrete as it traveled down the tube and into the basin. When concrete is discharged in water, the reduced kinetic energy decreases the relative velocity between the concrete and water, thus reducing the intermixing of concrete with water. Again, the bottom of the pipe was capped using a rubber-lined wooden plate secured to the pipe by wires. A photograph of the inclined tremie pipe is shown in Figure 39 (Appendix D).

In casting the MSFMPRO and HSFLPRO slabs, the pipe was partially filled with concrete and placed 12 in. from the front side of the basin and 6 in. above the base slab. The stationary pipe was then filled with concrete, and the end plate was removed to start casting. At the end of the first lift placement, the pipe was retrieved cleaned, sealed and positioned at the same location 2 in. above the surface of Lift A. These steps were repeated for casting the MSFMPRO concrete above water.

The inclined pipe was moved horizontally along the basin when casting the SLAGMPRO slab. The pipe end was first capped and positioned 9 in. from the end side of the box 5 in. above the base slab. One third of the concrete was delivered there, then the pipe was pulled horizontally backward without maintaining a seal to cast the other two

thirds of the concrete at the center and at 2 ft from the front side of the box. This sequence was repeated for placing lift B, except the pipe end was raised 2 to 6 in. above Lift A.

8.1.5 Sounding, Stripping and Coring Sounding data was collected at the conclusion of each pour to establish surface profiles. Surface elevations were mapped at 6 in. intervals along the basin and 7.5 in. intervals across the width, thus resulting in 65 readings per lift. One hour after casting the second lift, in order to divide the slab into four segments for examining flow patterns, three thin steel plates were gently forced into the fresh concrete through guides located directly above the step boundaries.

The one ton concrete slabs were cured under water for a few days then stripped for examination and coring. The concrete surface was photographed, and the mud thickness over the entire slab was mapped. The steel plates were then removed, thus dividing each large slab into four segments [A, B, C and D, with A being the front 2.5 ft portion of the slab (Figure 40, Appendix D)]. The resultant cross sections are referred to as sections I through V, with I being the front section, II being the interface between sections A and B, etc. The cross sections were examined to observe the flow patterns of the concrete over the step boundaries and examine the concrete for any segregated materials and voids there. The blocks were covered with wet burlap and plastic sheets until the coring program began.

A total of 12 cores measuring 3 in. in diameter were obtained from each slab. 20 cores were taken from the MSFMPRO-TREMIE slab. The cores were examined, logged, photographed then stored in a lime-saturated solution at 73 ± 3^0 F. Half of the cores were used to measure the density, f'_c and bond strength between Lifts A and B. The rest were used to examine the bond strength between the "new" and "old" concretes. The origin of the slab was considered to be the left-front corner of the slab. The X and Y locations refer to the distances from the origin across and along the slab, respectively.

8.1.6 Testing Hardened Concrete Control cylinders prepared on land were stored with their corresponding cored specimens. Density and f'_c values were tested between 99 and

110 days of curing. The density was determined by measuring the weight of the concrete above and under water. The unit weight values of core specimens were measured before and after cutting both ends of each core to remove loose and segregated materials.

Cut cores were then capped and tested in compression. Depending on the aspect ratio of the core, the tested strength was multiplied by a correction factor (ASTM-C 42). The core density and f'_c were compared to strength values of control cylinders. The bond strength was measured using the point-load tensile test (section 5.2.3).

8.2 Observations and Test Results

The evaluated properties of each of the nine slabs are described as follows:

8.2.1 Concrete Properties Tables 8 and 9 summarize the mix proportions of concretes cast using the tremie and inclined tremie pipes, respectively. The slump, flow, unit weight, air content and curing history as well as the compressive and splitting tensile strengths of control cylinders are tabulated. Important properties evaluated in the previous chapter pertaining to the performance of each mixture are emphasized.

8.2.2 Flow and Appearance The casting sequence and surface profiles of each lift are described. The step configurations and discharge locations are indicated on these plots to facilitate the envision of the concrete flow. The depths of the mapped concrete surface is expressed as the averages of readings recorded along the two sides, two quarter lengths and the center line of the slab. The time lag between casting the two consecutive lifts and the average flow and slump values are indicated on these plots. Pictures of the entire stripped slab and a selected cross section are also provided.

8.2.3 Unit Weight The measured density values of cut cores are plotted along the slab. The letters in parenthesis next to each data point identify the lift from which the core was obtained. For example, an A core indicates that the plotted data point was measured for a

concrete core taken from Lift A. The legend of the plotted points describes the location of the core across the slab. Cores drilled through the left, middle or right third sections across the slab are referred to with a black square, star or white circle legends, respectively. Core descriptions, coordinates and tested properties are also tabulated.

8.2.4 Compressive Strength Measured in-place f'_c values expressed as percentages of the control strength values are plotted. Legends used for density graphs are also adopted here. Core descriptions, locations, correction factors and f'_c values are tabulated.

Table 8. Mix Proportions and Properties of Concretes Placed with Tremie Pipes

MIXTURE PLACEMENT	CONTROL TREMIE	M3FMPRO TREMIE	HSFLPRO TREMIE	SLAGMPRO TREMIE	FAMPRO TREMIE
CEMENT, PCY	568	600	590	378	504
SILICA FUME, PCY	74	42	59	45	40
FLY ASH, PCY	28	30	30	0	126
BLAST FURNACE SLAG, PCY	0	0	0	252	0
TOTAL CM, PCY	670	672	679	675	670
W/CM	0.35	0.4[illegible]	0.38	0.43	0.41
SAND, PCY	1390	1365	1404	1335	1345
PEA GRAVEL, PCY	1650	1625	1670	1590	1600
HRWRA, FL OZ/100# CM	26	40	32	38	38
WRA, FL OZ/100# CM	5.5	0	5	0	0
AEA, FL OZ/100# CM	1	0	0	0	0
PROTEX AWA, % CM	0	0.35	0.15	0.35	0.35
DE-AIR, % CM	0	0.15	0.11	0.17	0.15
CaCl2, % CM	0	0	0	0.75	0
MIX A SLUMP, IN.	8.75	10.5	9.25	10	10.25
MIX B SLUMP, IN.	21.4	10	9.25	9.75	10
MIX A FLOW, IN.	8.75	21.25	22	21.8	22
MIX B FLOW, IN.	21.4	20.75	22	20.5	20.5
UNIT WEIGHT, PCF	146.9	146.8	149	144.8	145.8
AIR VOLUME, %	3.5	3.25	2.75	3.5	2.75
CURING IN WATER, DAYS	10	4	4	4	8
UNDER WET BURLAP, DAYS	11 - 39	5 - 7	5 - 24	5 - 13	9 - 20
LIME BATH, DAYS	40 - 109	[illegible] - 110	25 - 100	14 - 100	21 - 109
MIX A F'c, PSI	12095	8415	9260	8870	8395
MIX B F'c, PSI	10980	8440	9265	8520	8295
OLD CONCRETE F'c, PSI	8975	8540	7820	7820	8975
MIX A F't, PSI	1205	850	905	790	775
MIX B F't, PSI	1095	910	920	745	840
OLD CONCRETE F't, PSI	840	890	715	715	840

8.2.5 Bond Strength Measured bond strengths at selected locations along the slab are plotted. Similarly, point-load tensile strength values within the "old" and "new" concretes are shown. Core description, coordinates and measured strength results are tabulated.

8.2.6 Average Density and Compressive Strength Ratios Average density and f'_c measurements at various locations along each slab are plotted. These results are expressed as percentages of control values in order to normalize them and facilitate comparisons.

Table 9. Mix Proportions and Properties of Concretes Placed with Inclined Tremie Pipes

MIXTURE CAST IN WATER/AIR	SLAGMPRO IN WATER	HSFLPRO IN WATER	MSFMPRO IN WATER	MSFMPRO IN AIR
CEMENT, PCY	382	587	600	610
SILICA FUME, PCY	46	59	42	43
FLY ASH, PCY	0	29	30	30
BLAST FURNACE SLAG, PCY	255	0	0	0
TOTAL CM, PCY	683	675	672	683
W/CM	0.43	0.38	0.41	0.4
SAND, PCY	1350	1395	1355	1370
PEA GRAVEL, PCY	1605	1660	1615	1640
HRWRA, FL OZ/100# CM	36	32	38	39
WRA, FL OZ/100# CM	0	5	0	0
PROTEX AWA, % CM	0.35	0.15	0.35	0.35
DE-AIR, % CM	0.17	0.1	0.13	0.15
CaCl2, % CM	0.75	0	0	0
MIX A SLUMP, IN.	10.25	9.75	9.75	9.75
MIX B SLUMP, IN.	10.25	9.5	9.75	9.5
MIX A FLOW, IN.	21.3	22.75	21.3	21.5
MIX B FLOW, IN.	21.5	21.5	21.1	21
UNIT WEIGHT, PCF	146.4	148.2	145.8	147.7
AIR VOLUME, %	2.75	2.75	3.25	3
CURING IN WATER, DAYS	3	3	3	1
UNDER WET BURLAP, DAYS	4 - 5	4 - 18	4 - 18	2 - 3
LIME BATH, DAYS	6 - 103	19 - 102	19 - 102	4 - 102
MIX A F'c, PSI	9505	10135	8720	9515
MIX B F'c, PSI	9255	10280	8795	9590
OLD CONCRETE F'c, PSI	10400	10400	9980	7310
MIX A F't, PSI	910	1020	915	900
MIX B F't, PSI	825	930	815	935
OLD CONCRETE F't, PSI	865	865	975	840

8.3 CONTROL-TREMIE Slab

8.3.1 Mix Proportions (Table 8) The CONTROL concrete did not incorporate any AWA and was used as a bench mark. Its washout weight loss after three test drops in water measured 4.9 percent which was greater than the values of the other four selected concretes. The concrete mixtures used for casting Lift A and Lift B were identical, the former developed slightly higher strength values than the second one.

8.3.2 Flow and Appearance (Figure 20; Figures 41 and 42 of Appendix D) Figure 20 shows the discharge locations for casting Lift A and Lift B. In spite of its high slump and flow values, the CONTROL concrete proceeded slowly out of the pipe and did not spread well under water (as predicted in section 7.6.3). The flow stopped once the bottom of the pipe became submerged in freshly-placed concrete. The pipe had to be retrieved upward in order to complete the placement. Large mounds were formed at the tremie locations at the end of each casting. The first mound was removed to facilitate the casting of the subsequent layer. Steep surface slopes were obtained in all directions, especially near the discharge location. A relatively thin layer of concrete reached the last two segments of the basin. A soft layer of mud ranging between 0.1 to 0.3 in. in thickness was observed over the last segment of the slab (Figure 42, Appendix D). All cross sections revealed that the concrete flowed continuously over the step boundaries and did not result in any large entrapped voids.

8.3.3 Unit Weight (Figure 43 and Table 12 of Appendix D) A gradual decrease in concrete density was observed as the concrete spread away from the tremie location. This drop became sharp near the end of the slab. The steps seemed to interfere with the flow of the concrete, hence creating a turbulence zone and increasing water dilution. The density increase at the end of the slab due to the removal of laitance and segregated materials was as high as 1.4 percent, indicating that the concrete experienced some disturbance as it flowed

over the rising steps and into the second hole. Cores drilled through Lift B at the mid length of the block showed relatively large discrepancy in density (1.5 percen.). The flow of the first lift was terminated there and was believed to have resulted in mud deposits at the foot of the steep concrete surface. The intermixing of the mud with the second cast lift might have caused the large density spreads of Lift B concrete at the slab center.

8.3.4 Compressive Strength (Figure 44 and Table 13 of Appendix D) A sharp decrease in f'_c was observed as concrete flowed away from the tremie pipe. This drop was especially high between the pipe location and the middle of the slab. At the middle section where mud deposits were expected, the f'_c of cores drilled through both concrete lifts were slightly weaker than those extracted solely from Lift B.

8.3.5 Bond Strength (Figure 45 and Table 14 of Appendix D) Concrete placed under water developed adequate bond strength with "old" concrete. The average bond strength was approximately 325 psi and ranged between 55 and 67 percent of the point-load tensile strength of the "old" concrete. Mixes A and B seemed to be well cemented together. The bond strength between Lift A and Lift B of a core located near the discharge point tested 490 psi. The fractured surface propagated through both lifts in a jagged manner.

8.3.6 Average Density and Compressive Strength (Figure 21) Underwater-cast concrete suffered far greater reductions in f'_c than in density. This is because the decrease in density is primarily due to water erosion of cementitious materials and other fines which in turn affects the strength significantly. The maximum density loss 4 ft from the discharge point was 3.8 percent. On the other hand, the maximum recorded f'_c reduction was 47 percent, and the average decrease in f'_c throughout the slab was 29 percent. The large deterioration in concrete quality can be accounted to its low resistance to water dilution and lack of proper self-consolidation resulting from the high internal shear resistance.

8.4 MSFMPRO-TREMIE Slab

8.4.1 Concrete Properties (Table 8) Mixes A and B had identical mix proportions and similar strength values. These values were compatible with those of the "old" concrete. The MSFMPRO concrete had a washout mass loss of 2.9 percent after three test drops in water, which was the lowest of the five adopted mixtures. Its investigated underwater leveling, fluidity and cohesion were also superior.

8.4.2 Flow and Appearance (Figure 22; Figures 46 and 47 of Appendix D) Both lifts were cast by allowing concrete to initially fall 6 in. through water (Figure 22). Considering the configurations of the step boundaries, the concrete spread readily and formed relatively gentle surface profiles. The top lift flowed over the bottom one and into the second scour hole where it nearly flattened. Minor changes of concrete thickness were observed across the slab. The cross sections at step boundaries revealed that the flow of the concrete was continuous without the presence of any segregated materials or voids. No mud was deposited anywhere over the hardened slab.

8.4.3 Unit Weight (Figure 48 and Table 15 of Appendix D) In-place density was constantly high in the first half of the slab but dropped gradually toward the end. The cut/uncut increase in density was limited to 0.21 percent because of the absence of laitance. Unlike the CONTROL slab, cores cut through Lift A and Lift B at the foot of the first cast layer of concrete showed small spread in density measurements (0.6 percent).

8.4.4 Compressive Strength (Figure 49 and Table 16 of Appendix D) The f'_c values were fairly high and uniform along the slab. Strength values of some cores at the lower end of the slab were as high as those recorded near the tremie location. All measured values fit within a 5.5 percent band. The maximum spread between the f'_c values of concrete cast on land and underwater was approximately 600 psi. Cores extracted from the bottom lift were slightly weaker than those taken from the top lift. This may be due to

the greater disturbance caused by the rising steps that was experienced by the lower concrete lift.

8.4.5 Bond Strength (Figure 50 Table 17 of Appendix D) Underwater-cast concrete bonded well to the base slab. The bond strength varied from 52 to 69 percent of the point-load tensile strength of the "old" concrete and 69 to 81 percent of the point-load tensile strength of the "new" concrete. The average bond strength between Lift A and Lift B was 510 psi, which was close to the point-load tensile strength within either concrete. The fractured surface propagated through both lifts indicating the lack of a weakness plane.

8.4.6 Average Density and Compressive Strength (Figure 23) The average maximum density reduction along the slab was limited to 3.2 percent of control density. This value was 1.2 percent lower than the average density at the discharge location. The maximum drop in f'_c was 4.5 percent from the control strength, and the largest difference in average f'_c at any two locations along the slab was a negligible value of 200 psi.

8.5 HSFLPRO-TREMIE Slab

8.5.1 Concrete Properties (Table 8) Mix proportions and strength results of Mixes A and B were identical. The HSFLPRO mixture had 4.2 percent washout weight value after three test drops in water. The concrete spread well under water when tested for underwater leveling (section 7.6.3).

8.5.2 Flow and Appearance (Figure 24; Figures 51 and 52 of Appendix D) The casting of concrete started by positioning the pipe nose 6 in. over the surface of "old" concrete, then the pipe was raised 3.5 in. to pour the second lift (Figure 24). The concrete spread very well and formed gentle slopes in all directions. Its high susceptibility to water erosion caused some of the cement and other fines to migrate out of the concrete and form a colloidally suspended film of disturbed fines which was observed to spread rapidly ahead

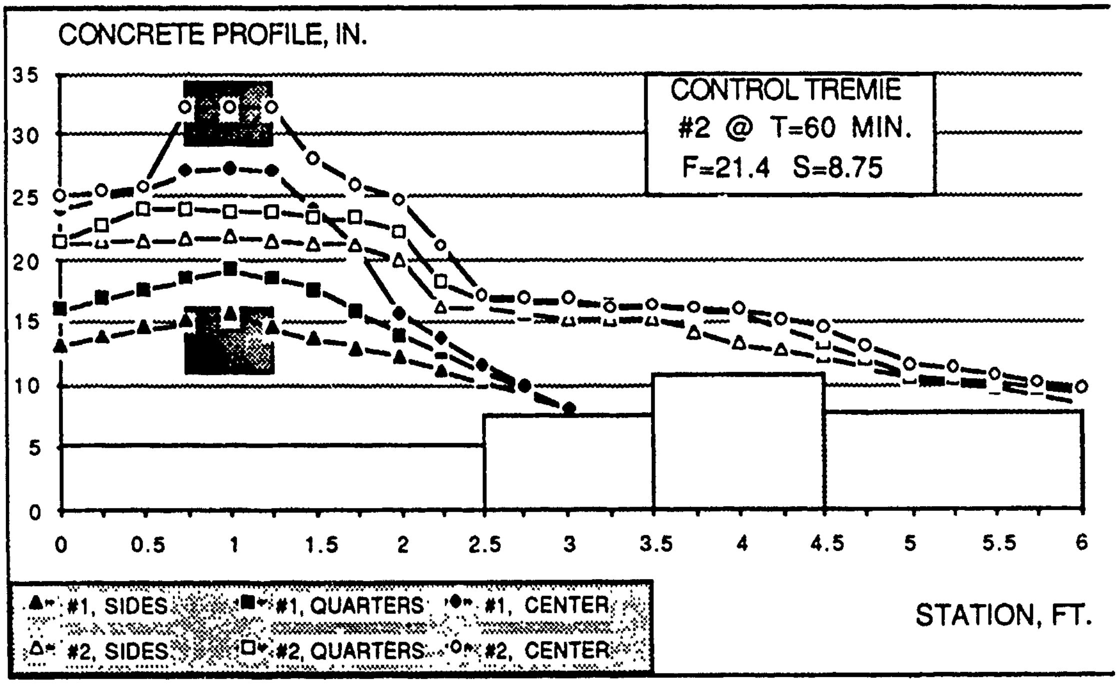


Fig. 20--Surface Profiles of the CONTROL-TREMIE Slab

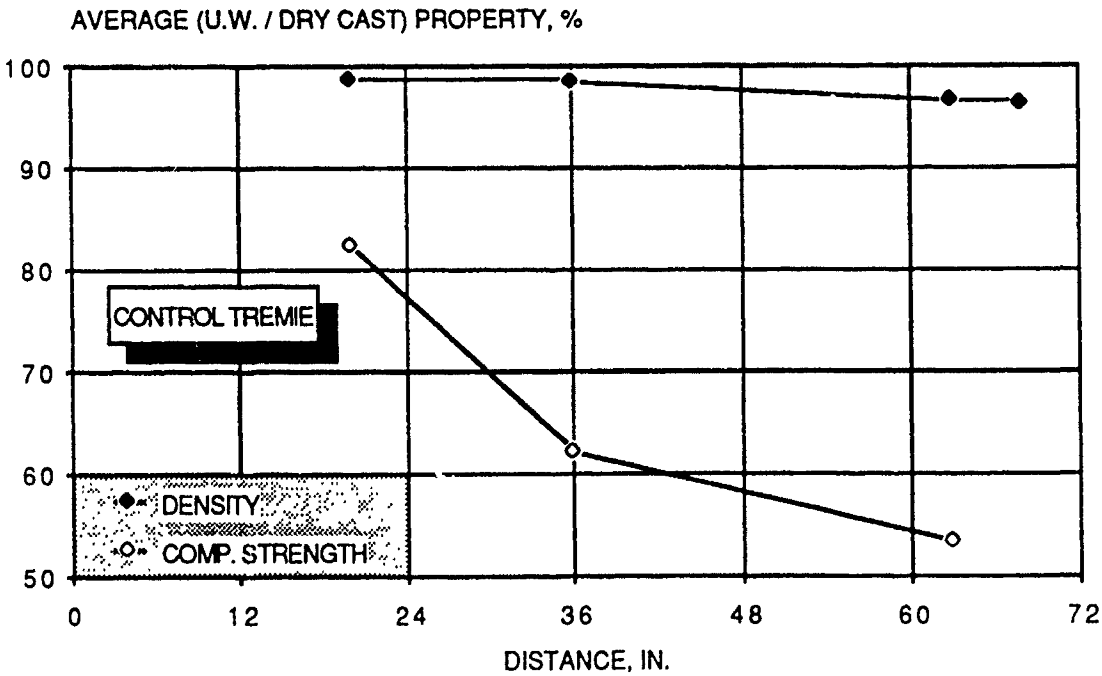


Fig. 21--Average Density and f'c Values along the CONTROL-TREMIE Slab

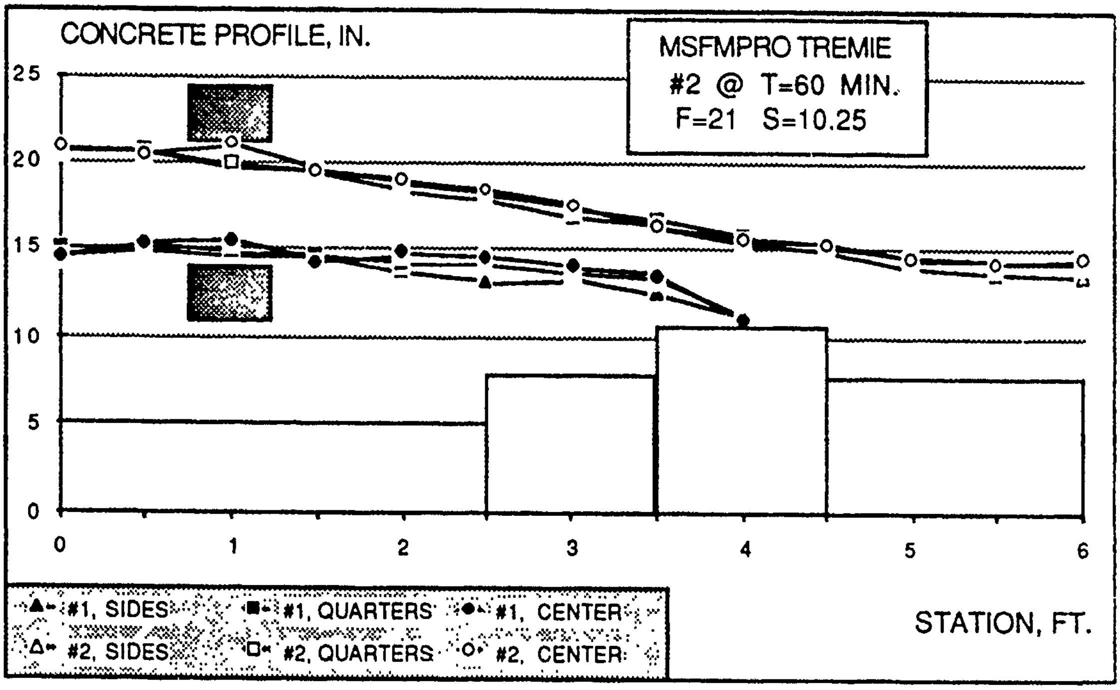


Fig. 22--Surface Profiles of the MSFMPRO-TREMIE Slab

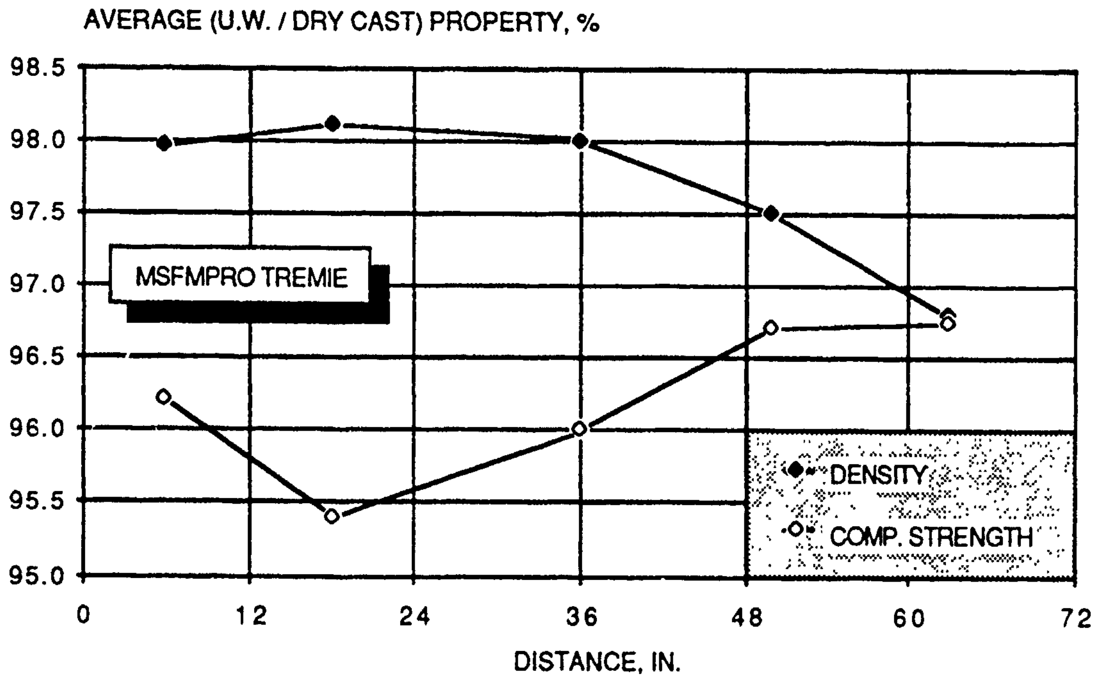


Fig. 23--Average Density and f'c Values along the MSFMPRO-TREMIE Slab

of the concrete away from the pipe. The laitance thickness over the four segments increased with the distance from the discharge location. The mud depth over each segment was as follows: 0.3 - 0.65 in. over block A, 0.65 - 0.8 in. over block B, 0.65 - 0.9 in. over block C and 0.7 - 1.1 in. over block D. The five cross sections in the concrete revealed that the concrete flowed continuously and did not result in any discontinuities.

8.5.3 Unit Weight (Figure 53 and Table 18 of Appendix D) The measured density values of the cores dropped gently in the first half of the slab but exhibited steeper losses in the second portion. Cores drilled through both lifts near the tremie location had lower densities than cores taken solely from Lift A. This can be due to the intermixing of laitance deposited on the surface of the first lift with the subsequent concrete lift. The cut/uncut increase in density ranged from 0.07 to 2.14 percent. The latter value was obtained at the end segment where the surface was covered with a relatively thick layer of mud.

8.5.4 Compressive Strength (Figure 54 and Table 19 of Appendix D) The average f'_c decreased substantially as concrete spread from the tremie pipe. The maximum drop was approximately 35 percent. The tested f'_c values were quite scattered. As observed with density measurements, cores drilled through both lifts had lower strength values than those extracted from either layer. This difference was especially large at the end of the first lift.

8.5.5 Bond Strength (Figure 55 and Table 20 of Appendix D) Despite laitance development, good bonding was obtained between the "new" and "old" concretes. The bond strength there varied from 320 to 400 psi, or 64 to 74 percent of the point-load tensile strength of the "old" concrete. The average bond strength at the joint between Lift A and Lift B was 430 psi near the discharge location.

8.5.6 Average Density and Compressive Strength (Figure 25): The average reduction in concrete density along the entire slab was 1.7 percent, and the average maximum loss in

density was 5.3 percent of the control value. The ultimate reduction in f'_c between the two ends of the slab was 25 percent.

8.6 SLAGMPRO-TREMIE Slab

8.6.1 Concrete Properties (Table 8) The mix proportions of Mixes A and B were identical, and their control strengths were similar to those of the "old" concrete. The concrete had a washout resistance of 4 percent after three test drops in water. The concrete had good cohesion and superior underwater leveling characteristics (section 7.6.3).

8.6.2 Flow and Appearance (Figure 26; Figures 56 and 57 of Appendix D) The concrete was initially dropped 6 in. and 2 in. to cast the first and second lifts, respectively. The concrete proceeded gently along the box without intermixing a lot with water. At the end of each placement, the nose of the tremie was still submerged into fresh concrete (Figure 26). The surface profile of Lift B was parallel to that of Lift A, and the lateral spread in concrete depth was very small. The maximum mud thickness over the slab was 0.1 inch. Cross sections at step boundaries revealed continuous flow and no void formation.

8.6.3 Unit Weight (Figure 58 and Table 21 of Appendix D) In-place concrete density was constant in the first half of the slab but gradually dropped toward the end. Unit weight measurements at any one station along the slab were uniform. The gain in concrete density due to cutting core ends ranged between 0.07 and 0.35 percent. The latter was observed at the end of the slab where a thin layer of loose fines was deposited.

8.6.4 Compressive Strength (Figure 59 and Table 22 of Appendix D) Unlike density measurements, the strength results were scattered. The f'_c values at any one station varied from 85 to 100 percent of the control strength. In general, cores drilled through Lift A achieved higher strength values than those taken from the top lift.

8.6.5 Bond Strength (Figure 60 and Table 23 of Appendix D) Underwater-cast concrete developed adequate bonding with "old" concrete. The bond strength varied from 53 to 65 percent of the point-load tensile strength of the "old" concrete and 72 percent of that of the "new" concrete. The average bond strength at the interface between Lift A and Lift B ranged between 355 and 410 psi. The fractured plane propagated mostly through Lift B.

8.6.6 Average Density and Compressive Strength (Figure 27) The average in-place concrete density in the first half of the slab was 2 percent lower than the control density. This value dropped to 3.3 percent 4 ft ahead of the discharge location. The average f'_c along the slab was 93.7 percent of the control value, and the maximum recorded drop in f'_c was 7.5 percent.

8.7 FAMPRO-TREMIE Slab

8.7.1 Concrete Properties (Table 8) The mix proportions of Mixes A and B were slightly different, their W/CMs were 0.41 and 0.42, respectively. The strength values were close and similar to those of the "old" concrete. The FAMPRO concrete had a relatively low washout weight loss of 3 percent after three test drops in water.

8.7.2 Flow and Appearance (Figure 28; Figures 61 and 62 of Appendix D) Lift A filled the first hole completely and resulted in flat surfaces. The second lift flowed parallel to the bottom one and into the second hole. The thickness of the concrete across the first lift was the same. However, a small spread in thickness across Lift B was observed. No mud was collected anywhere over the slab surface. All cross sections at step boundaries showed continuous concrete flow without any segregation or void formation.

8.7.3 Unit Weight (Figure 63 and Table 24 of Appendix D) The tested density values gradually decreased with the distance from the discharge point. A slight discrepancy in

concrete densities was observed at some locations, however, that spread was limited to 0.7 percent. The maximum recorded cut/uncut increase in density was 0.07 percent.

8.7.4 Compressive Strength (Figure 64 and Table 25 of Appendix D) A slight decrease in f'_c was observed at the middle of the slab where cores drilled through Lift A had 2 to 3 percent lower f'_c than those taken from the upper lift. The reduced strength of the bottom lift could have resulted from greater intermixing with water caused by the larger initial drop distance in water at the begining of placement and greater disturbance caused by the rising steps. In-place f'_c values at the end of the slab were almost as high as those tested near the discharge location. All strength values fit within a narrow band, the maximum difference in tested f'_c values along the slab was limited to 500 psi.

8.7.5 Bond Strength (Figure 65 and Table 26 of Appendix D) Underwater-cast concrete bonded well to the "old" concrete. The measured bond strength varied from 66 to 77 percent of the point-load tensile strength of the "old" concrete and 68 to 76 percent of that of the "new" concrete. The bond strength was especially high near the discharge location (410 psi). The average bond strength between Lift A and Lift B was 435 psi. The fractured plane propagated through both lifts in a jagged manner indicating good bonding.

8.7.6 Average Density and Compressive Strength (Figure 29) The maximum loss of average in-place density along the slab was limited to 0.75 percent, or approximately 2 percent reduction from the control value. The average in-place f'_c along the entire slab was approximately 7,600 psi, and the highest spread in average f'_c at any single station was limited to 200 psi. The maximum average drop in f'_c was a relatively large value of 10.5 percent of the control f'_c value.

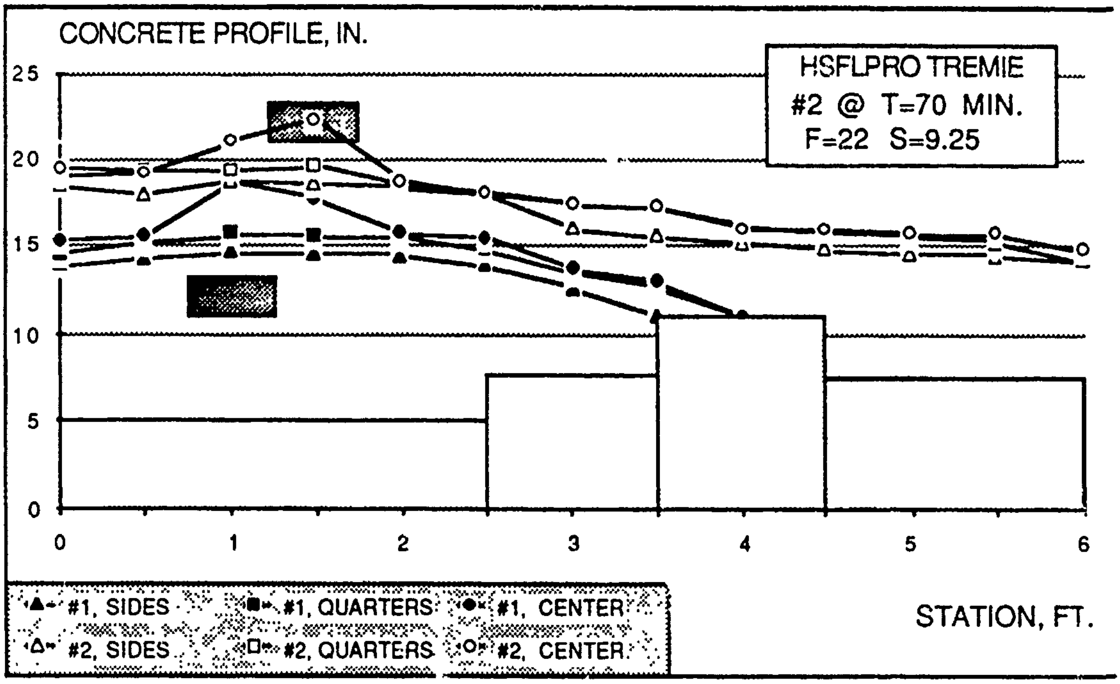


Fig. 24--Surface Profiles of the HSFLPRO-TREMIE Slab

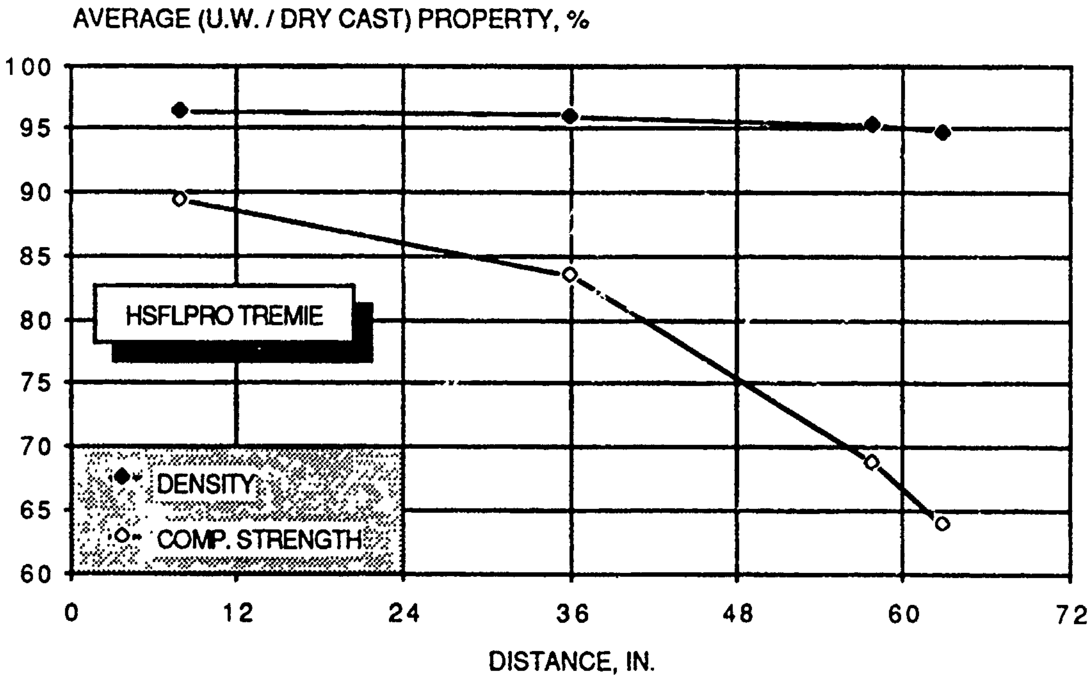


Fig. 25--Average Density and f'_c Values along the HSFLPRO-TREMIE Slab

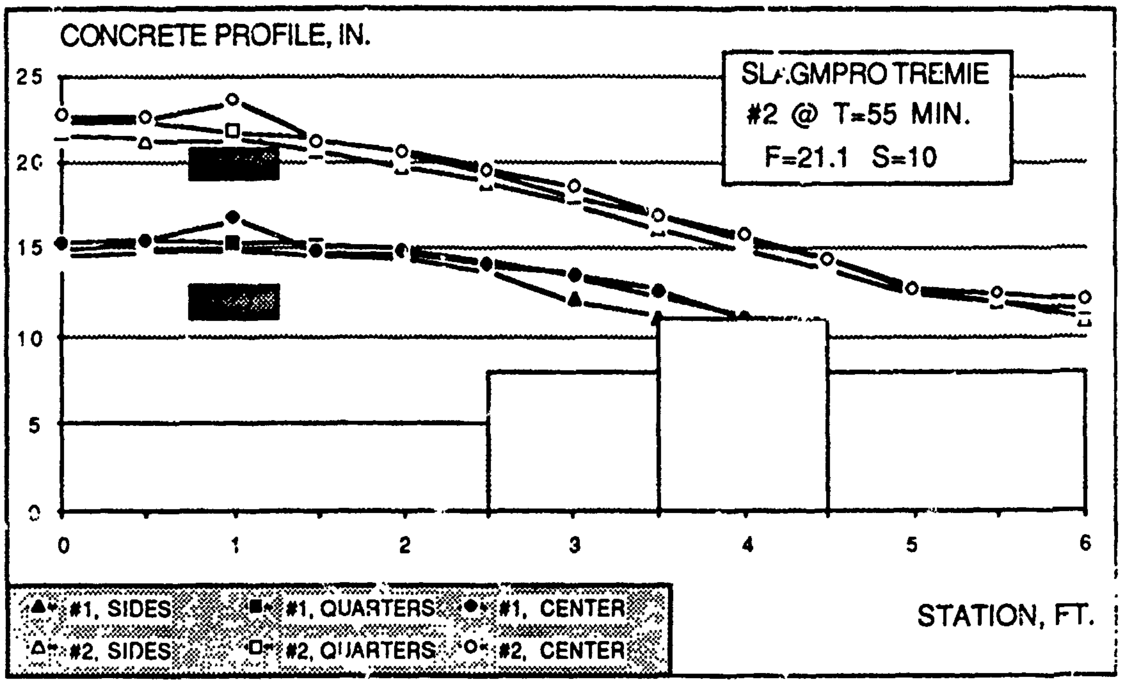


Fig. 26--Surface Profiles of the SLAGMPRO-TREMIE Slab

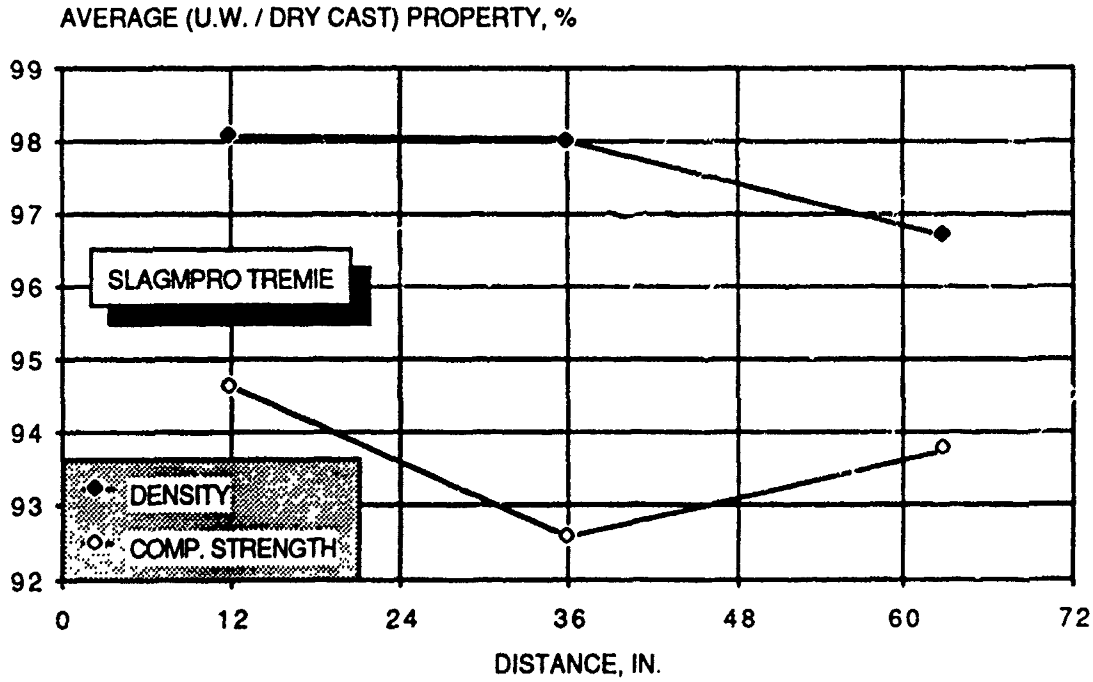


Fig. 27--Average Densities and f'$_c$ Values along the SLAGMPRO-TREMIE Slab

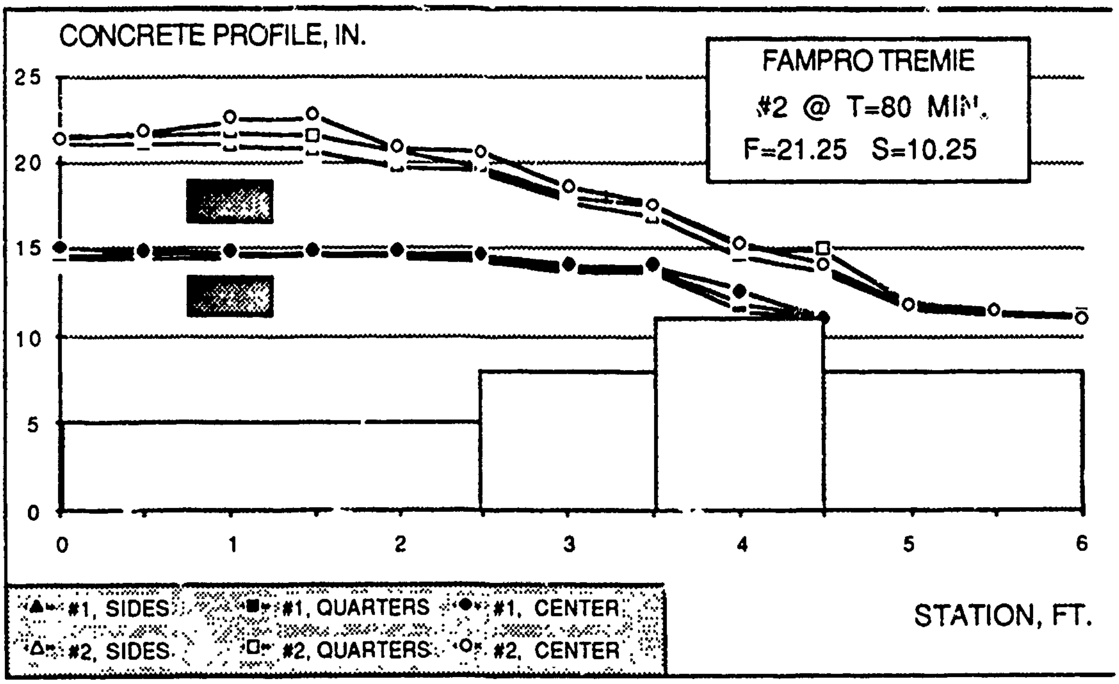


Fig. 28--Surface Profiles of the FAMPRO-TREMIE Slab

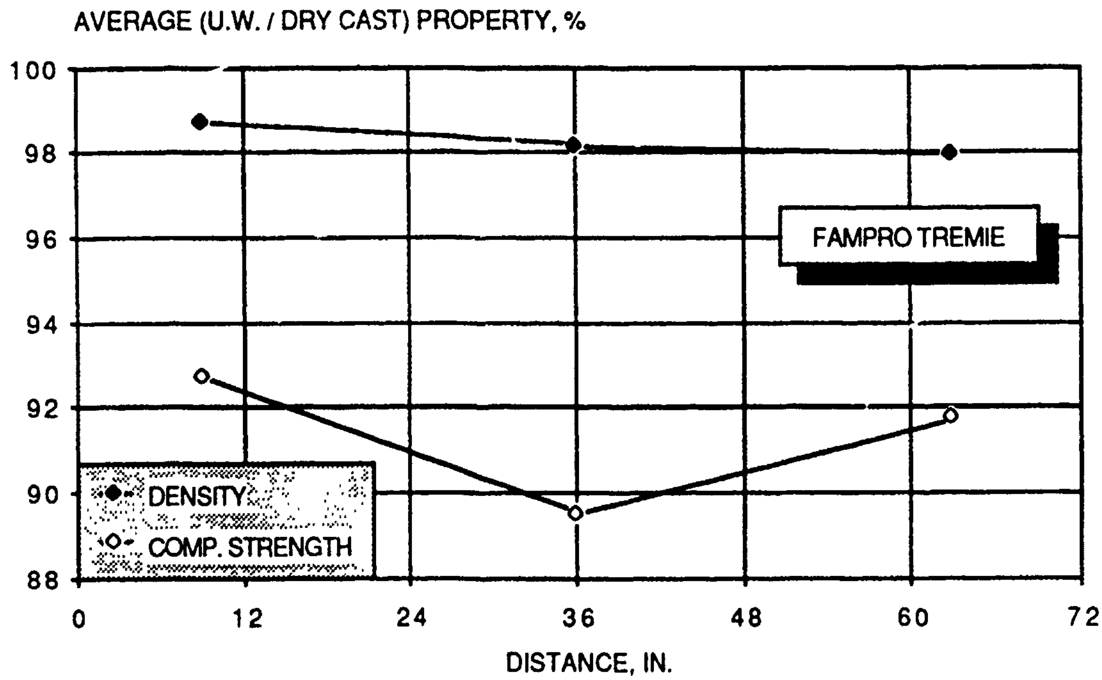


Fig. 29--Average Densities and f'_c Value along the FAMPRO-TREMIE Slab

8.8 SLAGMPRO-INCLINED TREMIE Slab

8.8.1 Concrete Properties (Table 9) The mix proportions of both concrete lifts were identical, and their strength values were similar and compatible to those of the "old" concrete. The mix design of this concrete was similar to that of the SLAGMPRO-TREMIE slab. The air content was 0.75 percent less than that obtained with the tremie-cast one which resulted in higher strength values.

8.8.2 Flow and Appearance (Figure 30; Figures 66 and 67 of Appendix D) As described in section 8.1.4, the inclined tremie pipe was dragged backward through water to cast similar volumes at three locations along the basin. As shown in Figure 30, the first lift was discharged at locations A1, A2 and A3. Similarly, the casting of the subsequent lift started at B1 and ended at B3. The end of the pipe was sealed at the start of each lift (locations A1 and B1). However, the seal was not maintained when the pipe was moved in water.

In spite of the high level of water exposure, a small amount of fines was observed, and no mud was deposited over the slab. As expected, the surface slopes were rather flat since concrete was discharged throughout the placement box. A small lateral spread in concrete thickness was observed. The cross sections showed continuous concrete flow over step boundaries without voids or segregated materials.

8.8.3 Unit Weight (Figure 68 and Table 27) The tested concrete density along the slab differed only by 0.5 percent. Slightly higher densities were measured at the front of the slab, location B3, despite the high drop in water. The cut/uncut increase in density ranged from 0.07 to 0.48 percent and was uniform along the slab.

8.8.4 Compressive Strength (Figure 69 and Table 28) The f'_c results at any single location were scattered because of the increased disturbance and water dilution caused by

the movement of the pipe in water. This disturbance was magnified by the rising steps near the middle of the slab which increased water dilution.

8.8.5 Bond Strength (Figure 70 and Table 29) The underwater-placed material developed good bond strength with "old" concrete which ranged from 275 to 445 psi. These values correspond to 51 - 86 percent of the point-load tensile strength of the "old" concrete and 69 - 86 percent of the point-load tensile strength of the "new" concrete. The bond strength between "old" and "new" concretes was lowest near the boundaries of the second hole. The average bond strength between Lift A and Lift B tested approximately 350 psi, and the fractured plane propagated through both layers in a jagged manner.

8.8.6 Average Density and Compressive Strength (Figure 31) The average density values along the slab were nearly constant. The average density of all tested cores was approximately 98 percent of control density. The maximum spread in average f'_c values along the slab was limited to 500 psi, or 4.6 percent of the control f'_c. The largest reduction in average f'_c from the control value was 9.2 percent.

8.9 HSFLPRO-INCLINED TREMIE Slab

8.9.1 Concrete Properties (Table 9) Both concrete lifts had similar mix proportions, air contents and unit weights. Their strength values were consistent and compatible with those of the "old" concrete.

8.9.2 Flow and Appearance.(Figure 32; Figures 71 and 72 of Appendix D) Mix A filled the first hole completely, and the second lift flowed parallel to the first one resulting in a relatively thick slab at the end. Surface slopes were relatively gentle. A small lateral spread in concrete thickness was observed, and no laitance was collected anywhere along the slab. The cross sections did not reveal any discontinuity as the concrete flowed over the step boundaries.

8.9.3 Unit Weight (Figure 73 and Table 30 of Appendix D) In-place concrete density was constant in the first half of the basin and slightly decreased toward the end. The maximum loss in density was limited to 2.2 percent. The cut/uncut density increase was relatively small (0.2 $\pm$ 0.05 percent).

8.9.4 Compressive Strength (Figure 74 and Table 31 of Appendix D) A steep drop in f'_c was observed in the first half of the slab. Individual test results were scattered, especially at the end of the slab. Three cores were tested at the end of the slab, two of which suffered 3 percent f'_c reductions and the third tested a 14 percent strength drop.

8.9.5 Bond Strength (Figure 75 and Table 32 of Appendix D) Concrete placed under water developed good bonds with "old" concrete. The bond strength ranged from 310 to 370 psi, or 51 to 64 percent of the point-load tensile strength of the "old" concrete and 53 to 64 percent of the point-load tensile strength of "new" concrete. Good bonding was also measured at the interface between Lift A and Lift B where the average bond strength at the middle of the slab was 425 psi. The fractured plane at that interface propagated through both lifts indicating good bonding.

8.9.6 Average Density and Compressive Strength (Figure 33) The slab showed a mild decrease in density in the direction of the flow. The maximum drop in density was 2.9 percent from the control density, which was one percent lower than the average in-place density of cores taken near the discharge location. The slab suffered a sharp deterioration in f'_c at the first half of the basin where an approximate 8 percent average reduction was recorded 2 ft from the discharge point. The average f'_c at the end of the basin was comparable to that recorded at its center, however, as discussed earlier a large spread in results was observed there. The average f'_c of all tested cores was 95 percent of the control strength.

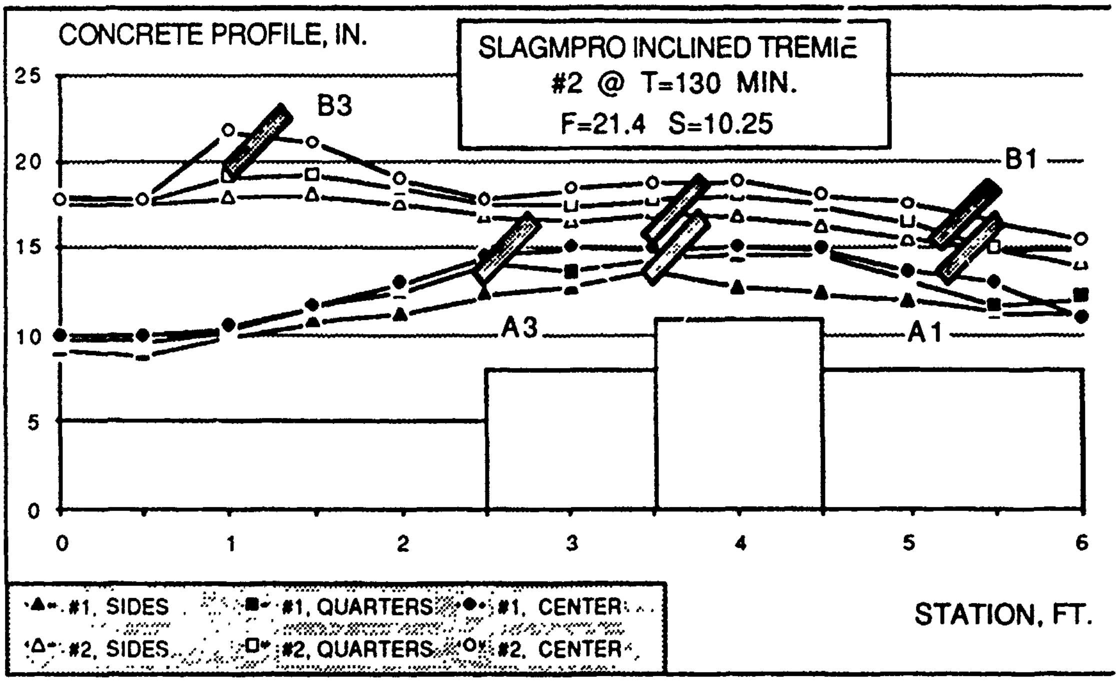


Fig. 30--Surface Profiles of the SLAGMPRO-INCLINED TREMIE Slab

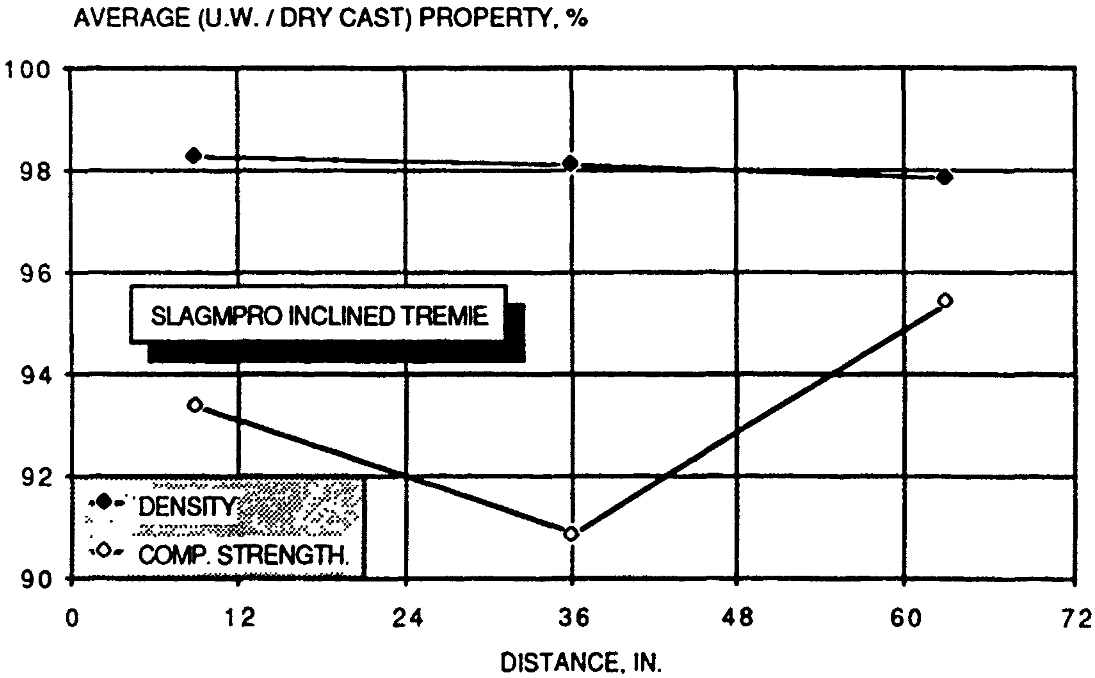


Fig. 31--Average Density and f_c Values of the SLAGMPRO-INCLINED TREMIE Slab

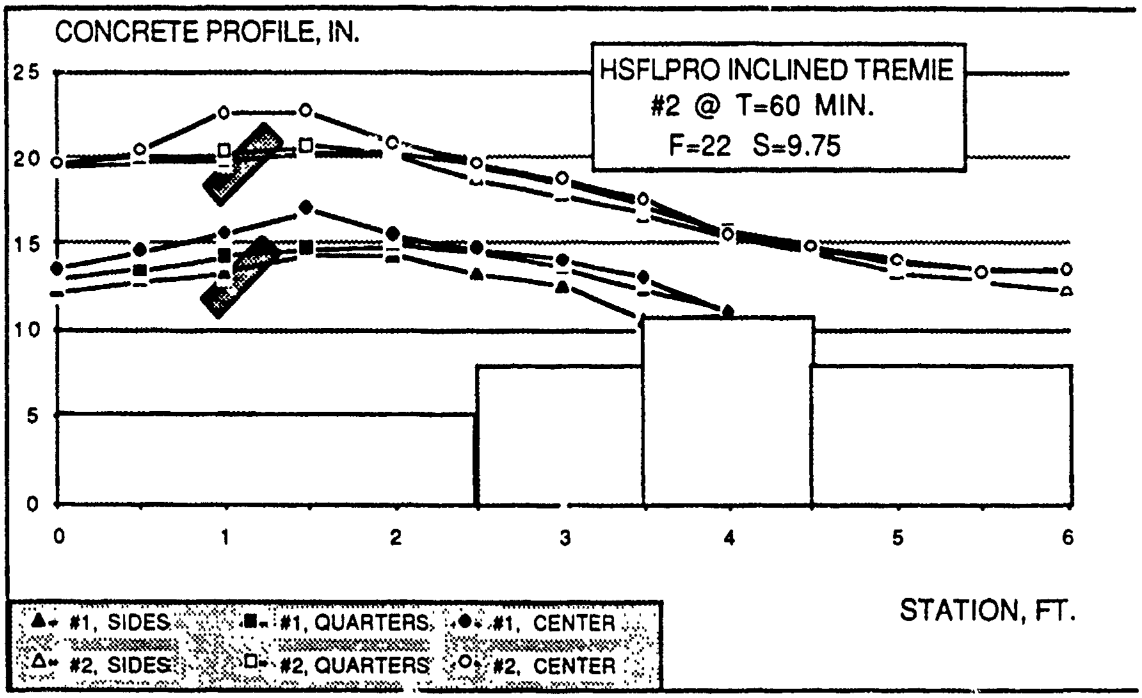


Fig. 32--Surface Profiles of the HSFLPRO-INCLINED TREMIE Slab

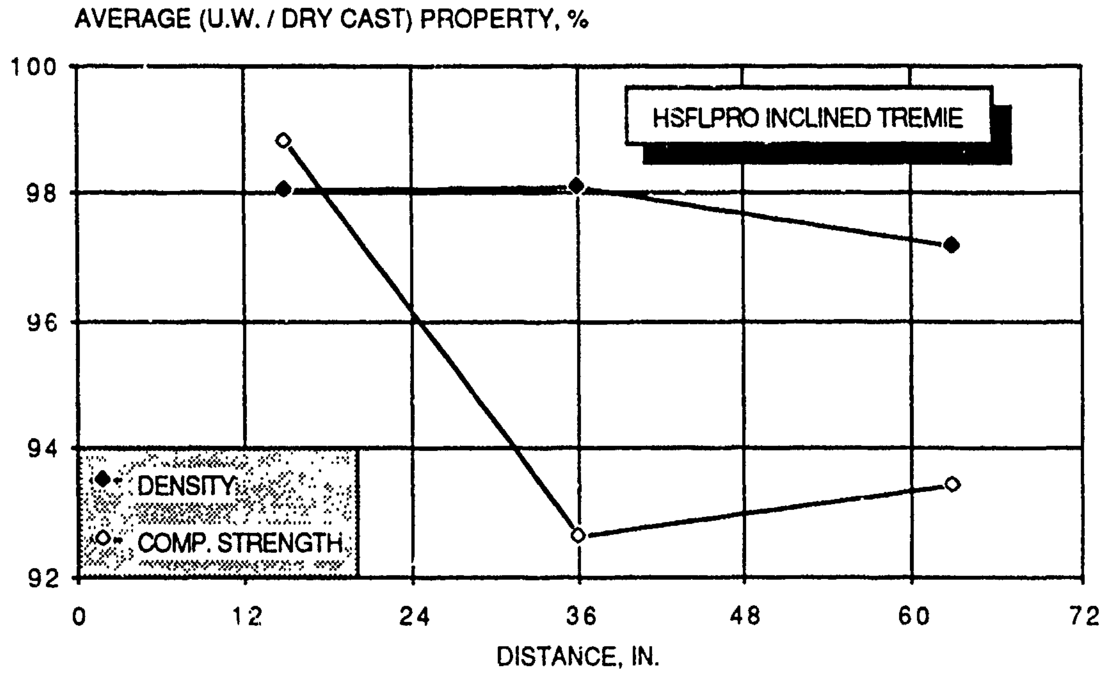


Fig. 33--Average Density and f'_c Values of the HSFLPRO-INCLINED TREMIE Slab

8.10 MSFMPRO-INCLINED TREMIE Slab

8.10.1 Concrete Properties (Table 9) The mix proportions of Mixes A and B were identical. Both concretes had the same air content, unit weight and strength values.

8.10.2 Flow and Appearance (Figure 34; Figures 76 and 77 of Appendix D) The same steps used in casting the HSFLPRO-INCLINED TREMIE slab were adopted here. Mix A completely filled the first hole and self-leveled nicely. The second layer flowed parallel to the bottom one, then flattened out at the end of the box developing a relatively thick segment there. The surface slopes were gentle, and only a small lateral spread in concrete thickness was observed. No mud was deposited anywhere along the slab. Cross sections at step boundaries showed continuous concrete flow without any voids or segregated materials.

8.10.3 Unit Weight (Figure 78 and Table 33) The density of concrete decreased gradually in the direction of the flow. The maximum tested reduction in density at the end of the slab was 2.4 percent. The cut/uncut density increase was limited to 0.13 percent, except for one value of 0.48 percent near the discharge location.

8.10.4 Compressive Strength (Figure 79 and Table 34) A constant reduction in f'_c was observed along the slab. The maximum spread of any two measured f'_c values along the slab was limited to 550 psi.

8.10.5 Bond Strength (Figure 80 and Table 35) Underwater-cast concrete secured good bonding to the "old" concrete. The bond strength ranged from 325 to 430 psi, or 46 to 83 percent of the point-load tensile strength of the "old" concrete and 66 to 88 percent of the point-load tensile strength of the "new" concrete. High bond strength was also tested at the interface between the two lifts. The average bond strength there was 450 psi, and the fractured surface propagated through both lifts.

8.10.6 Average Density and Compressive Strength (Figure 35) Average density and f'_c values showed similar drops along the slab. The reductions in density ranged between 0.4 and 2.4 percent of the control density. The average in-place f'_c values near the tremie pipe and at the end of the slab were 96.9 and 93.7 percent, respectively. The actual difference between these two values was 280 psi only.

8.11 MSFMPRO-INCLINED TREMIE DRY-CAST Slab

8.11.1 Concrete Properties (Table 9) Mix proportions of both concrete lifts were identical. Both concretes had similar fluidity, air content and strength values.

8.11.2 Flow and Appearance (Figure 36; Figures 81 and 82 of Appendix D) The two concrete lifts were placed following the same procedures used in casting the MSFMPRO-TREMIE slab, except the placement box was not filled with water. The concrete flowed readily out of the inclined pipe. However, the flow of the concrete slowed down as the depth of concrete decreased inside the pipe and the end of the pipe became submerged in fresh concrete. The pipe had to be slightly raised to complete the placement.

The flow of concrete through the inclined pipe seemed to proceed faster at the upper portion of the pipe which was not always filled with concrete. The higher friction between the viscous concrete and the bottom portion of the pipe is believed to be the cause for the slower flow at the bottom. This resulted in higher concentration of mortar at the bottom of the pipe and high amount of coarse aggregate flowing on top. The mortar seemed to back flow and spread behind the pipe causing loose materials to be deposited there. This observation confirms the findings of the other underwater placements with inclined tremie pipes where aggregate particles were found on the top surface of the slabs and high concentrations of mortar were deposited behind the pipe locations.

Mix A filled the first hole, and the second layer flowed parallel to it and became flat at the end of the box. A small lateral spread in concrete thickness was observed, and no

laitance was collected anywhere along the slab surface. The cross sections showed continuous flow of concrete over step boundaries without any signs of segregation.

8.11.3 Unit Weight (Figure 83 and Table 36 of Appendix D) Core density measurements were scattered at all stations along the slab, however, the difference between average values at different locations was limited to one percent of control density. Unlike other concretes, some of the cores tested higher density values than the control concrete which was fully compacted. The highest and lowest density values were 100.6 and 98.2 percent, respectively, of control density. The increase in density caused by cutting core ends was limited to 0.40 percent.

8.11.4 Compressive Strength (Figure 84 and Table 37 of Appendix D) The in-place f'_c of cores near the discharge location showed a maximum spread of 700 psi. All tested f'_c values ranged between 101 and 93.8 percent of control strength.

8.11.5 Bond Strength (Figure 85 and Table 38) Both concrete lifts developed superior bonding to the "old" concrete. The bond strength ranged from 455 to 560 psi. This corresponded to 95 ± 10 percent of the point-load tensile strength of the "old" concrete and 85 percent of the point-load tensile strength of the "new" concrete. High bond strength was also secured at the interface between Lift A and Lift B. This value averaged 445 psi, or approximately 80 percent of the point-load tensile strength of Mixes A and B. The failure plane propagated through both layers in a jagged manner.

8.11.6 Average Density and Compressive Strength (Figure 37) The average in-place density of tested cores was only 0.6 percent lower than that of control concrete. The average f'_c decreased uniformly in the first 4 ft, then showed a 1.3 percent increase toward the end. The maximum and minimum average f'_c values along the slab were 96.9 and 94.6 percent of control strength, respectively, or an actual strength of 220 psi.

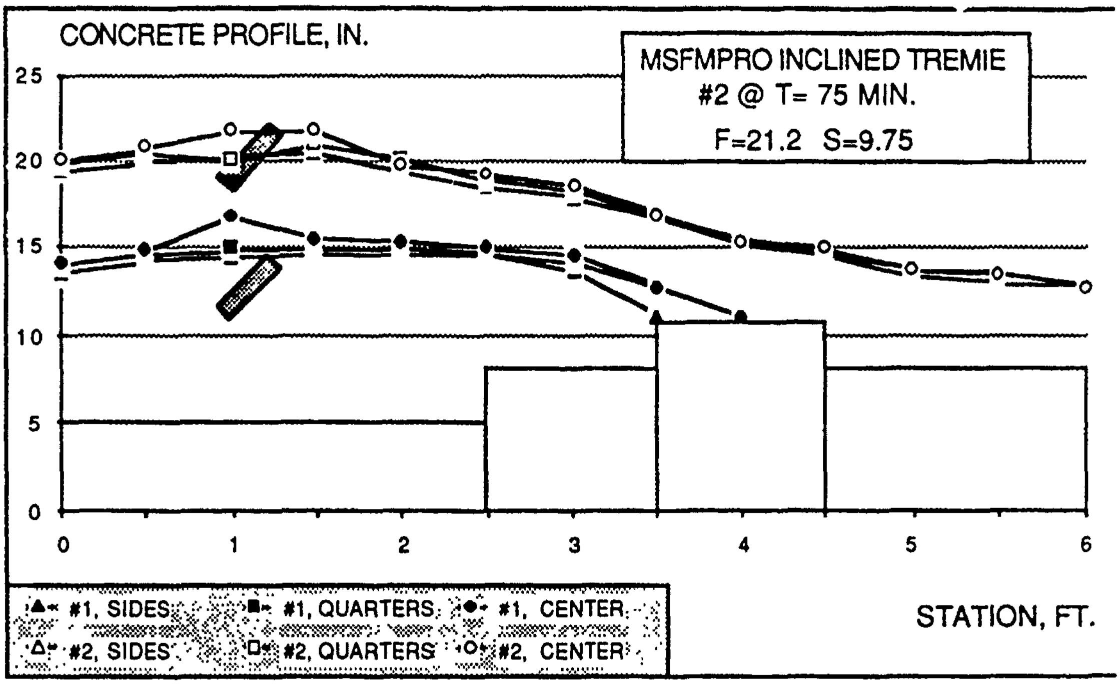


Fig. 34--Surface Profiles of the MSFMPRO-INCLINED TREMIE Slab

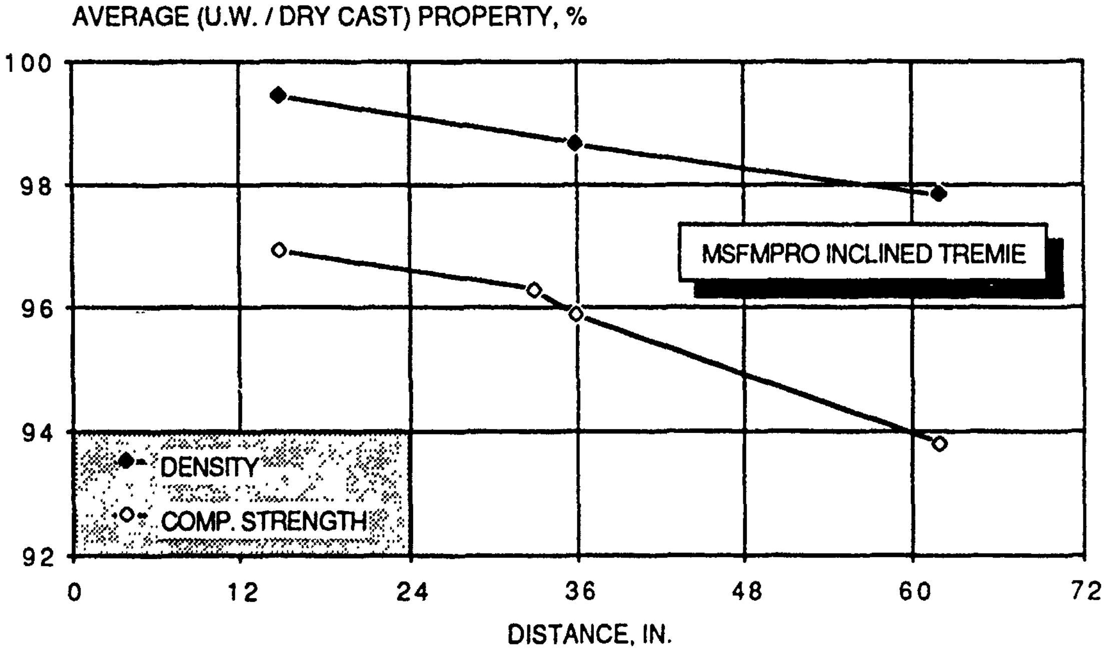


Fig. 35--Average Density and f'_c Values of the MSFMPRO-INCLINED TREMIE Slab

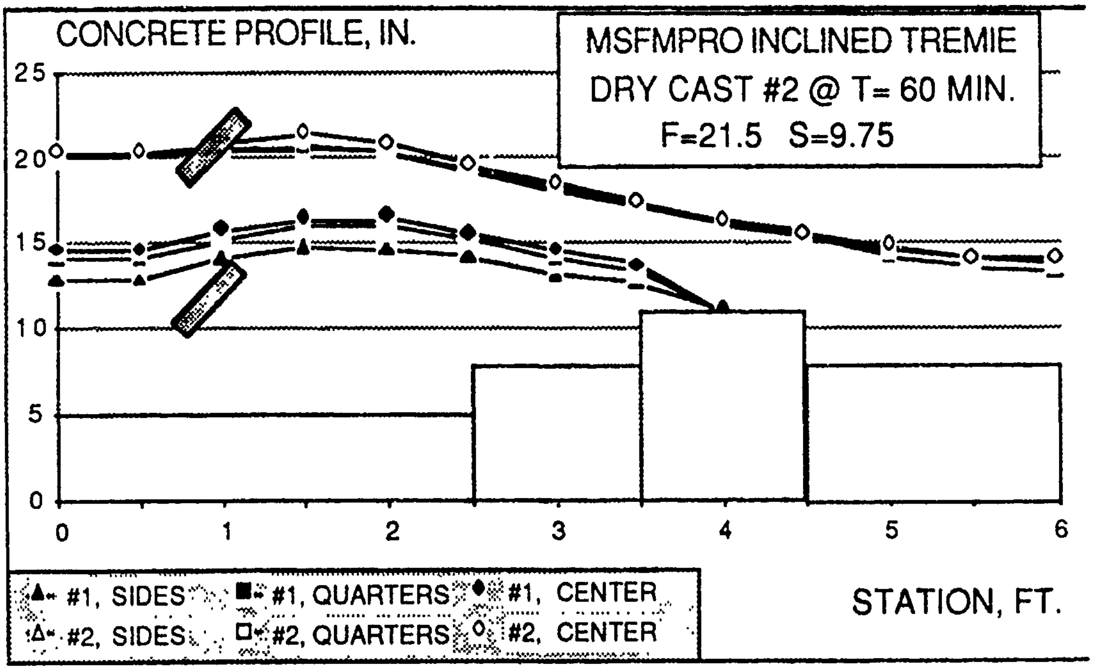


Fig. 36--Surface Profiles of the MSFMPRO-INCLINED TREMIE DRY-CAST Slab

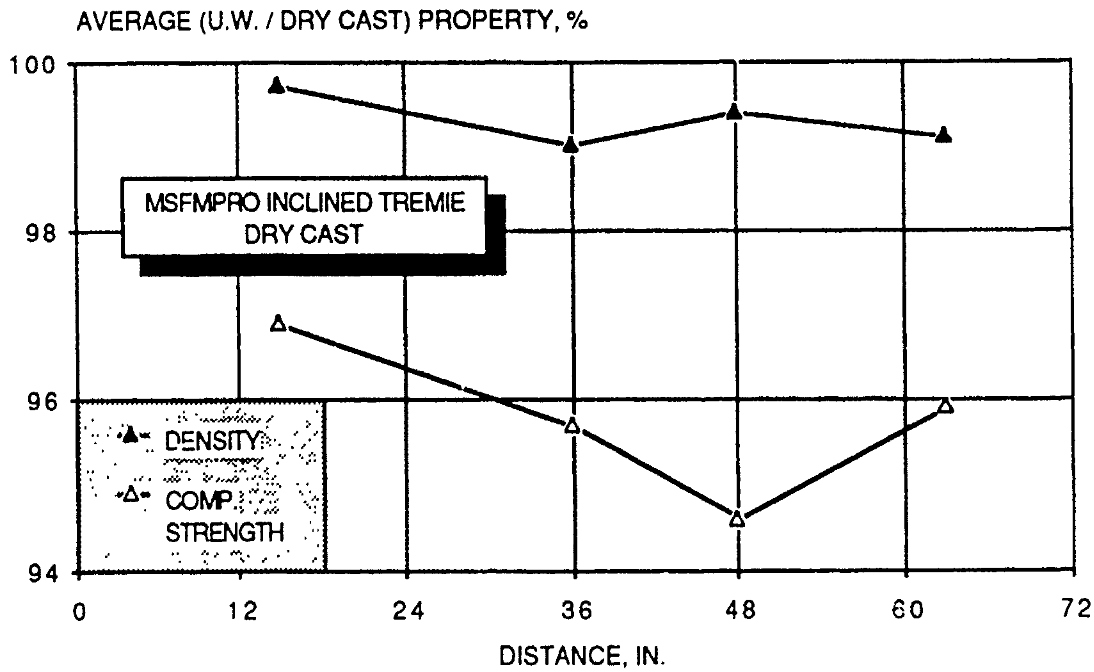


Fig. 37--Average Density & f'c along MSFMPRO-INCLINED TREMIE DRY-CAST Slab

8.12 Comparison of the Five Selected Concretes

Table 10 summarizes the average density and f'_c results for all nine concrete slabs, while Table 11 lists all the tested bond strengths. The depth of laitance and increase in densities due to the removal of loose and segregated materials from core ends are also tabulated. Highlighted values in these tables refer to favorable results.

8.12.1 Concretes Placed with Conventional Tremie Except for the CONTROL mixture, the other concretes had acceptable and similar surface profiles. The HSFLPRO slab had the most favorable flow profile, but it experienced a lot of disturbance when cast in water and developed the thickest mud layer.

Average density and f'_c measurements of the five tremie-cast slabs are plotted in Figures 38 and 39. All five concretes showed similar rates of density reductions. Apart from the HSFLPRO slab, which resulted in the lowest in-place density, the average core densities throughout the other tremie-cast concrete slabs were 97.8 $\pm$ 0.5 percent of their control values. The FAMPRO concrete maintained the highest average density throughout the slab (98.3 percent). Unlike the rest of tremie-placed concretes, its density did not decrease beyond the mid length of the slab. The hardened concrete did not have any mud and showed the lowest gain in density due to the removal of core ends. Although the FAMPRO concrete had favorable density values, it suffered approximately 2.5 to 5 percent more reduction in f'_c than the MSFMPRO and SLAGMPRO concretes. The average actual strength of the FAMPRO slab was 7,595 psi versus 8,170 and 8,140 psi for the other concretes, respectively. The CONTROL and HSFLPRO slabs experienced sharp drops in f'_c which were 44 and 34 percent, respectively, 4 ft from the discharge location.

The MSFMPRO and SLAGMPRO slabs had similar overall density values (approximately 97.5 percent). The greater washout resistance of the former concrete resulted in slightly greater relative density values, lower laitance formation and smaller cut/uncut density gains than the SLAGMPRO concrete. The relative f'_c values of the

MSFMPRO and SLAGMPRO slabs were relatively constant throughout the slabs. The former concrete maintained 1 to 3.25 percent higher f'_c values than the other one. The overall average f'_c of the MSFMPRO concrete was 96.2 percent, or 8,170 psi, while the f'_c of the SLAGMPRO concrete had an average strength 93.7 percent, or a similar average strength of 8,140 psi.

The MSFMPRO concrete is considered to be slightly superior because of its gentler surface profiles and its ability to secure greater relative density and strength values. Moreover, the measured strength results were more consistent than those of the SLAGMPRO concrete. The MSFMPRO mixture secured the highest average bond strengths at the interface between "old" and "new" concrete (380 psi), as well as between the two consecutive lifts (510 psi).

<u>8.12.2 Concretes Placed with Inclined Tremie</u> Average measured mechanical properties of concrete slabs cast with inclined pipes are shown in Figures 40 - 42. The placement pipe was held stationary for casting the MSFMPRO and HSFLPRO slabs but was moved horizontally along the placement box for casting the SLAGMPRO slab. The movement of the pipe resulted in smaller changes in average densities along the SLAGMPRO slab than the other two slabs. The spread between density values at both ends of the SLAGMPRO slab was limited to 0.5 percent. The MSFMPRO concrete had the highest relative in-place density throughout the slab (98.6 percent).

The SLAGMPRO concrete had the highest in-place average f'_c at the end of the basin where the casting was initiated, however, the strength decreased as the pipe was moved backwards without maintaining an end seal. Both the SLAGMPRO and MSFMPRO slabs tested similar average in-place f'_c values over the entire slab (8,675 and 8,375 psi, respectively). The latter exhibited the least reduction in relative strength along the slab, its average f'_c was 95.7 percent of its control strength.

Because of its lower resistance to water erosion, the HSFLPRO slab had greater reductions in density and sharper drops in f'_c than the other concretes. However, its high control f'_c (10,200 psi) resulted in an average in-place f'_c of 9,730 psi (94.9 percent of control) which was greater than those attained with the other two concretes.

All three concretes cast under water with an inclined tremie pipe yielded high quality surfaces. However, because of its greater resistance to water dilution, the MSFMPRO mixture exhibited superior performance. The MSFMPRO concrete developed the highest average bond strengths between the "new" and "old" concretes and between Lift A and Lift B (370 and 450 psi, respectively). The slab did not have any mud at its surface and had the lowest increase in density due to core end removals.

Table 10. Summary of Average Densities and Compressive Strengths

TREMIE	CONTROL	MSFMPRO	HSFLPRO	SLAGMPRO	FAMPRO
MAX. AVG. DENSITY, %	98.5	98	96.4	98	**98.7**
MIN. AVG. DENSITY, %	96.2	96.8	94.7	96.7	**98**
AVG. SLAB DENSITY %	**97.3**	**97.4**	95.6	**97.6**	**98.3**
MAX. AVG. F'c, %	82.3	**96.7**	89.4	94.6	92.7
MIN. AVG. F'c, %	53.4	**95.4**	63.8	92.6	89.5
AVG. SLAB F'c, %	65.9	**96.2**	76.4	93.7	91.3
AVG. SLAB F'c, PSI	7480	**8170**	7075	**8140**	7595

INCLINED TREMIE	SLAMPRO	HSFLPRO	MSFMPRO	MSFMPRO DRY CAST
MAX. AVG. DENSITY, %	**98.3**	98.1	99.4	**99.7**
MIN. AVG. DENSITY, %	**97.8**	97.1	97.8	**99**
AVG. SLAB DENSITY %	**98**	**97.8**	**98.6**	**99.3**
MAX. AVG. F'c, %	95.4	**98.8**	**96.9**	**96.9**
MIN. AVG. F'c, %	90.9	92.6	**93.8**	**94.6**
AVG. SLAB F'c, %	93.2	**94.9**	**95.7**	**95.8**
AVG. SLAB F'c, PSI	**8675**	**9730**	**8375**	**9175**

Table 11. Summary of Bond Strengths and Laitance Thicknesses

TREMIE	CONTROL	MSFMPRO	HSFLPRO	SLAGMPRO	FAMPRO
BOND RANGE "NEW"/"OLD", PSI	300 - 375	335 - 450	320 - 400	290 - 330	325 - 410
AVG. BOND, PSI (# CORES)	335 (4)	**380 (5)**	365 (3)	320 (5)	355 (5)
% OLD/OLD	55 - 67	52 - 69	64 - 74	63 - 65	66 - 77
% NEW/NEW	- -	69 - 81	- -	72	68 - 76
BOND RANGE LIFT A/B, PSI	490	485 - 515	430	355 - 410	430 - 440
AVG. BOND, PSI (# CORES)	490 (1)	**510 (3)**	430 (1)	390 (3)	435 (2)
RANGE MUD THICKNESS, IN.	0.1 - 0.3	0	0.3 - 1.05	0.05 - 0.1	0
CUT/UNCUT INCREASE, %	0 - 1.4	0 - 0.21	0.07 - 2.14	0.07 - 0.35	0 - 0.07
AVG. CUT/UNCUT INCREASSE, %	0.45	**0.09**	0.72	0.22	**0.02**

INCLINED TREMIE	SLAGMPRO	HSFLPRO	MSFMPRO	MSFMPRO DRY CAST
BOND RANGE "NEW"/"OLD", PSI	275 - 445	310 - 370	325 - 430	455 - 560
AVG. BOND, PSI (# CORES)	340 (5)	335 (4)	**370 (5)**	**505 (7)**
% OLD/OLD	51 - 86	51 - 64	46 - 83	85 - 105
% NEW/NEW	67 - 86	53 - 57	66 - 88	85 - 89
BOND RANGE LIFT A/B, PSI	335 - 365	415 - 430	435 - 460	425 - 465
AVG. BOND, PSI (# CORES)	350 (4)	425 (2)	**450 (3)**	**450 (4)**
RANGE MUD THICKNESS, IN.	0	0 - 0.2	0	0
CUT/UNCUT INCREASE, %	0.07 - 0.48	0.15 - 0.27	0.01 - 0.48	0 - 0.40
AVG. CUT/UNCUT INCREASSE, %	0.24	0.2	**0.11**	**0.14**

8.13 Underwater-cast Versus Dry-cast Concretes

The MSFMPRO concrete was cast under water and above water using an inclined tremie pipe to determine the extra deterioration caused by casting the concrete in water. Both dry-cast and underwater-cast concrete mixtures had identical slump and flow values and were cast without any external consolidation. Both slabs did not have any laitance at their surfaces and showed similar density increases due to the removal of segregated materials. The surface profiles of both slabs were similar, and the maximum difference in concrete thickness was limited to 0.75 in. at any location along the two slabs. Therefore, it appears that the reduced buoyant weight of underwater-cast concrete did not affect its spreadability when placed in such small volumes in areas containing obstacles that can impair the flow. Perhaps, the reduced driving force of underwater-placed concrete is

partially offset by the decreased internal shear resistance and added fluidity of the fresh concrete when cast in water.

As shown in Figure 40, the relative density of the dry-cast slab was consistently higher than the other concrete. This difference was especially large away from the discharge location. The marginal reduction of the in-place density that is caused by the combined effects of water dilution and reduced self-compaction varies between 0.3 and 1.2 percent. The average in-place relative density values of the the dry-cast and underwater-cast slabs were 99.3 and 98.6 percent, respectively, of control values. Unlike the latter slab which exhibited constant reduction in density along the slab, the dry-cast slab had uniform decrease in density along the first half of the slab and slight increase toward the end. This improvement could be the result of added consolidation caused by the end wall of the placement box.

The dry-cast MSFMPRO slab had a more favorable curing history and a slightly lower W/CM than the underwater-cast one. As a result its control f'_c was 9 percent higher than the underwater-cast mixture (9,555 versus 8,760 psi). The reduction in average f'_c of both concretes were similar along the slabs, except for approximately 2 percent strength increase at the end of the dry-cast slab. This increase can also be caused by local densification at the end wall which can occur without any added disturbance and water erosion. The average relative f'_c values of the entire dry-cast and underwater-cast slabs were identical (95.8 percent).

The lack of washed out and settled fines between "new" and "old" concretes resulted in substantial enhancement in bond development. The average bond strengths between "new" and "old" concretes of dry-placed and underwater-cast concretes were 505 and 370 psi, respectively. The latter strength was one of the highest values among the eight underwater-cast slabs. The highly fluid concrete appeared to intermix thoroughly when cast in consecutive layers. The average bond strengths at the interface of Lift A and Lift B for both dry-cast and underwater-cast concretes were identical (450 psi).

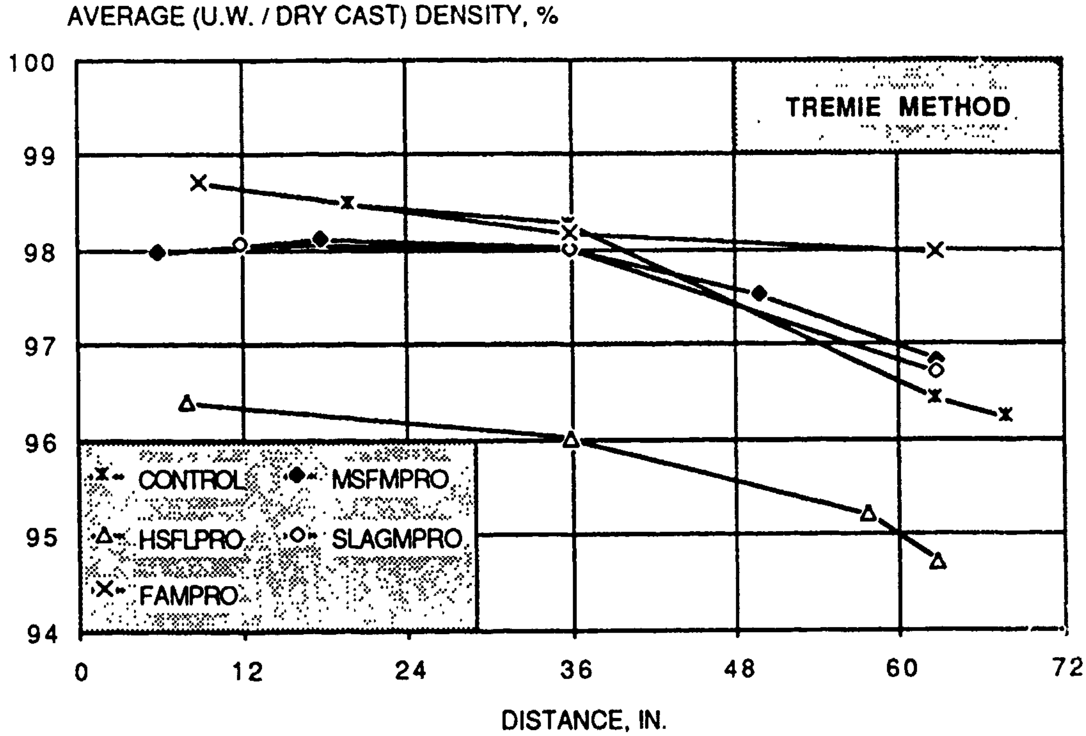


Fig. 38--Average Densities along Tremie-cast Slabs

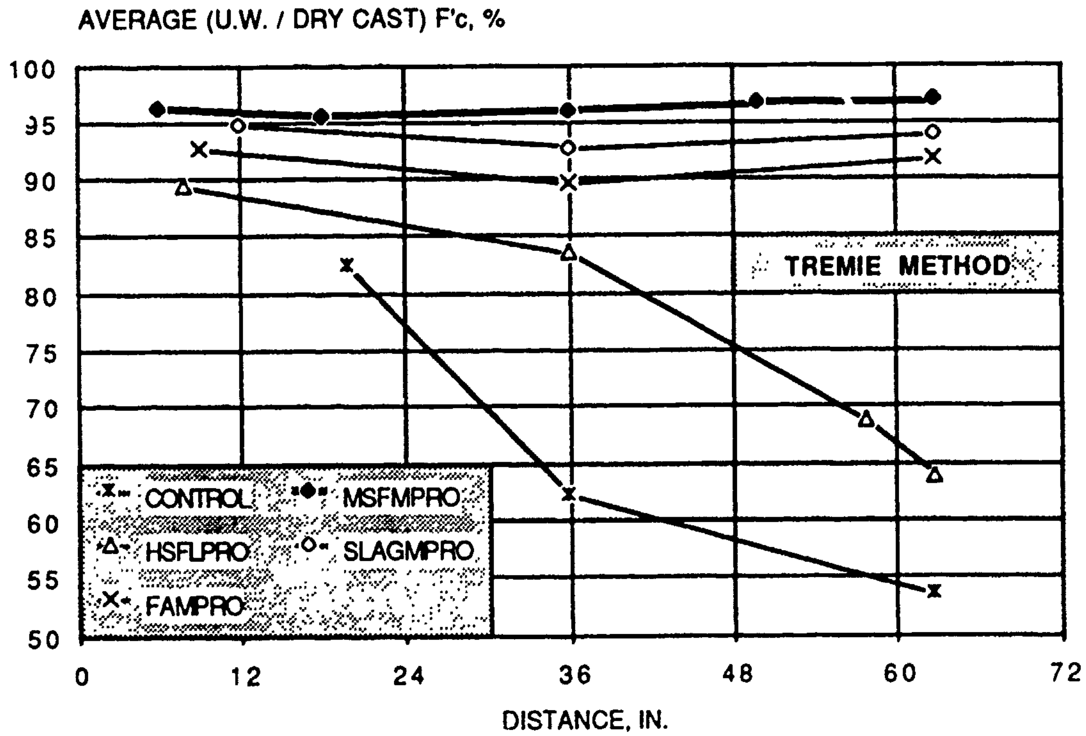


Fig. 39--Average Compressive Strengths along Tremie-cast Slabs

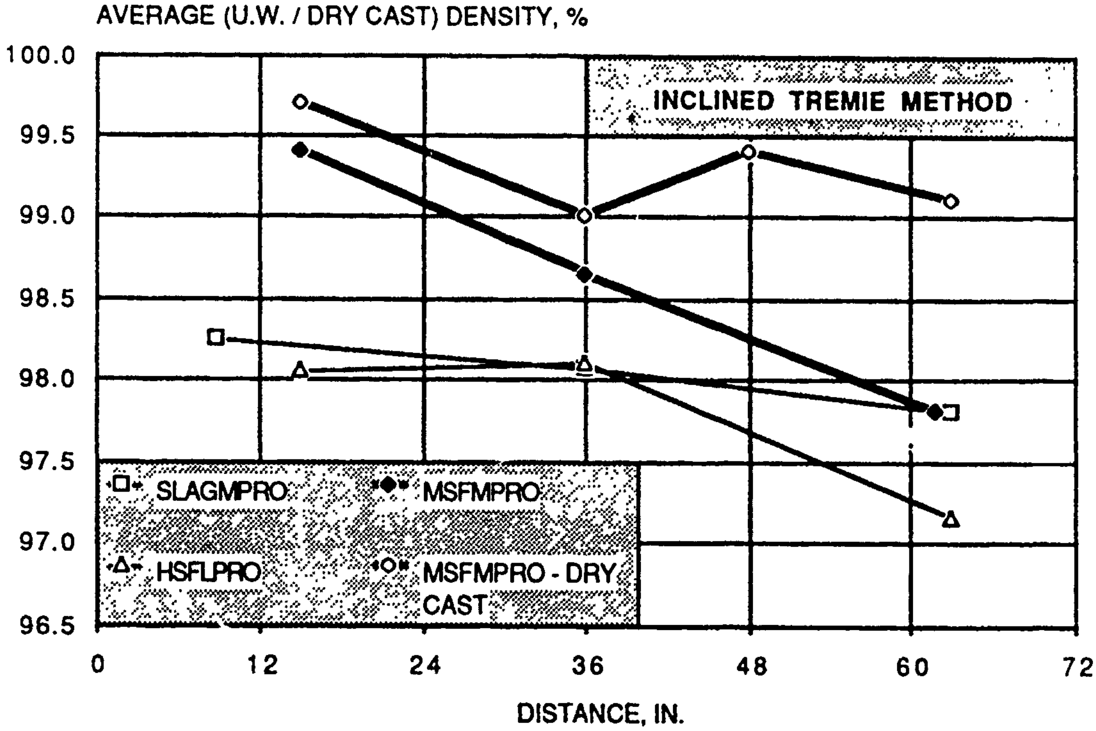


Fig. 40--Average Densities along Inclined Tremie-cast Slabs

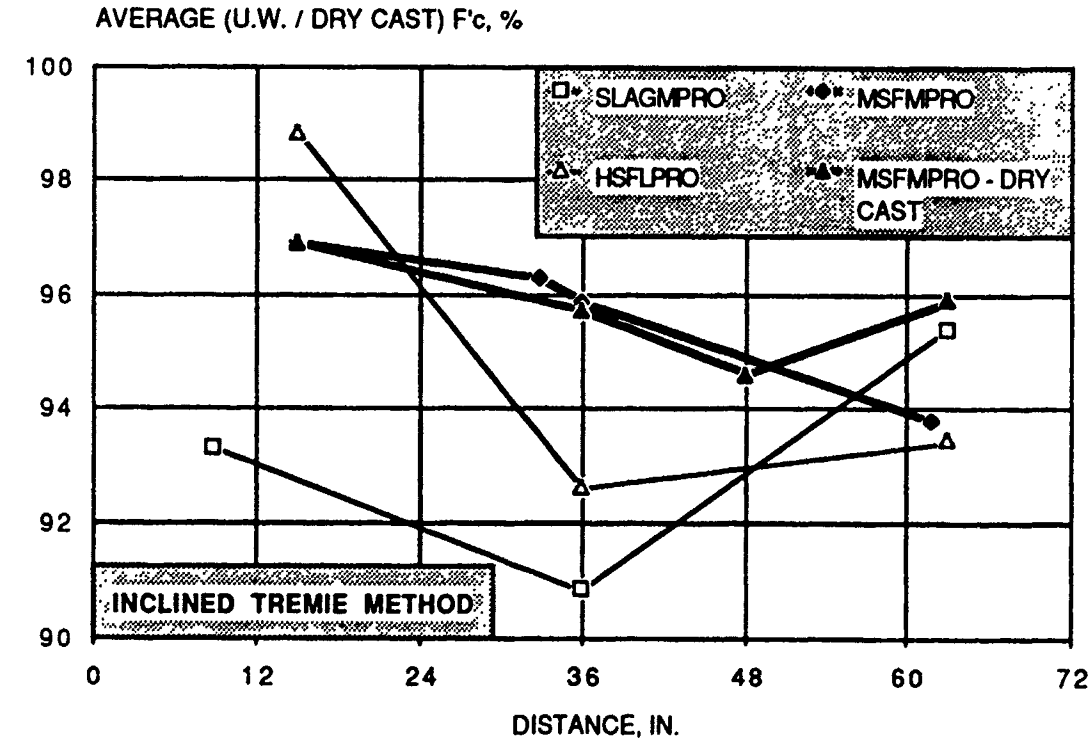


Fig. 41--Average Compressive Strengths along Inclined Tremie-cast Slabs

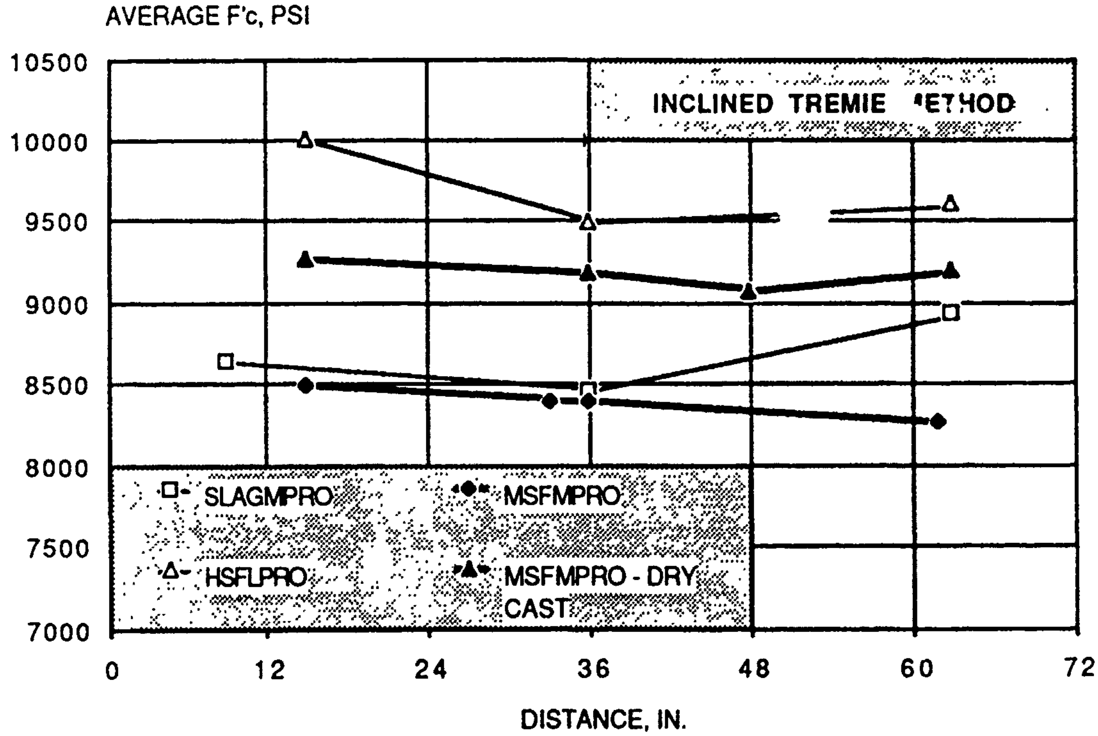


Fig. 42--Actual Compressive Strengths along Inclined Tremie-cast Slabs

8.14 Comparing Tremie to Inclined Tremie Methods

The ability of the placement technique to reduce segregation and water dilution was examined for vertical and inclined tremie methods by comparing the properties of three concretes cast under water using both methods.

The greatest advantage of implementing a 45^0 inclined pipe was exhibited with the HSFLPRO concrete. Concretes used for both placements had identical mix proportions and air contents. The HSFLPRO concrete performed poorly when cast using a vertical tremie pipe. However, the average in-place density of this concrete was considerably improved when an inclined pipe was implemented. Both slabs exhibited the same rates of density reductions, with the inclined slab maintaining 2.3 percent higher densities throughout the length of the slab (Figure 43). The inclined tremie-cast slab had far less laitance at its surface and an average of 3.6 times less increase in density due to core end

removals than the tremie-cast slab. Its in-place f'_c tested approximately 10 percent greater in the first half of the slab. This spread became greater as concrete spread further in water away from the discharge location. The inclined tremie slab had approximately 30 percent higher in-place f'_c than the regular tremie-cast slab at the end of the slab (Figure 44). The average relative f'_c of the entire tremie and inclined tremie slabs were 76.4 and 94.9 percent, respectively, or 7,075 and 9,730 psi. Both slabs tested similar bond strengths.

The average in-place density and f'_c values of the two MSFMPRO slabs are plotted in Figures 45 and 46, respectively. Both mix proportions were identical and the concrete had the same air contents and washout resistance values. The in-place density of the inclined tremie slab was higher than that of the tremie-cast slab, especially near the discharge location. The average in-place density values over the entire tremie and inclined tremie slabs were 97.4 and 98.6 percent, respectively. The average relative f'_c was approximately 96 percent of control values for either slab, and the spread between the actual average f'_c values was limited to 200 psi. Neither slab had any laitance or segregated materials at its surface. Both concretes developed high bond strengths with the base slab (370 - 380 psi). The average bond strengths between Lift A and Lift B of the tremie and inclined tremie slabs were 510 and 450 psi, respectively.

The average in-place density and f'_c values of the two SLAGMPRO slabs are plotted in Figures 47 and 48, respectively. The relative density of the incline tremie slab was higher than the vertical tremie one. The spread between the relative f'_c results of both slabs varied by approximately 2 percent at all tested locations. This was small considering the high spread of individual strength measurements obtained with either slab. Concrete cast with an inclined tremie was subjected to more water dilution and disturbance than the other concrete because of the movements of the pipe in water. Yet the average f'_c values of both slabs were approximately 93.5 percent of their control strengths. Both concretes had small mud developments and similar bond strengths.

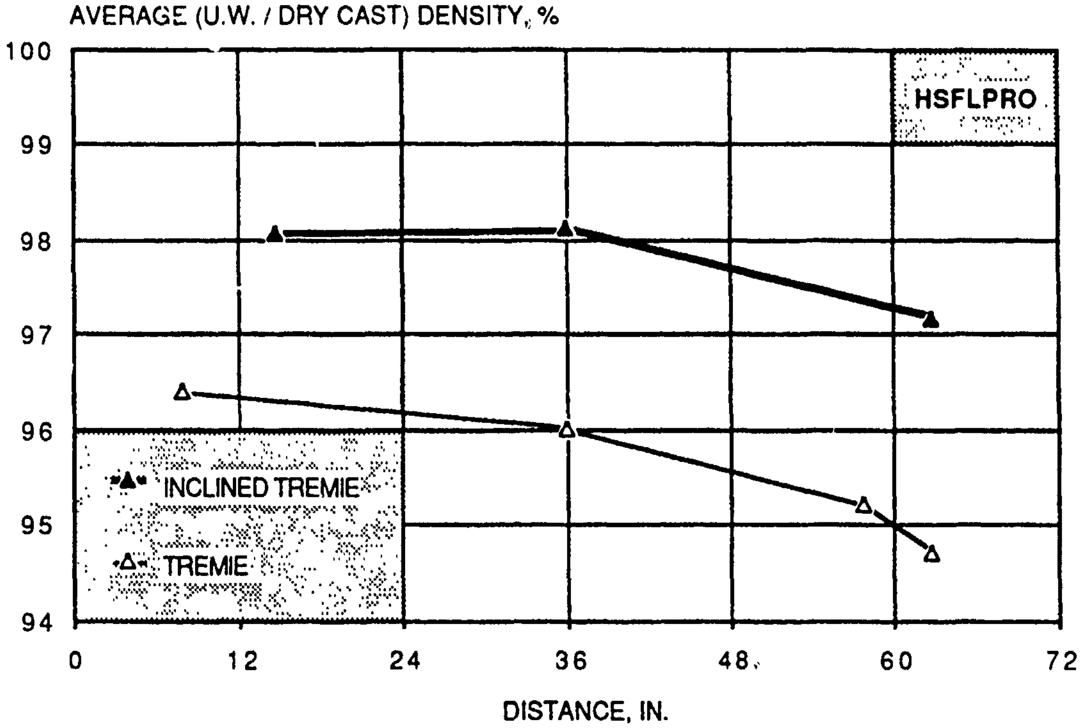


Fig. 43--Average Density Values along the HSFLPRO Slabs

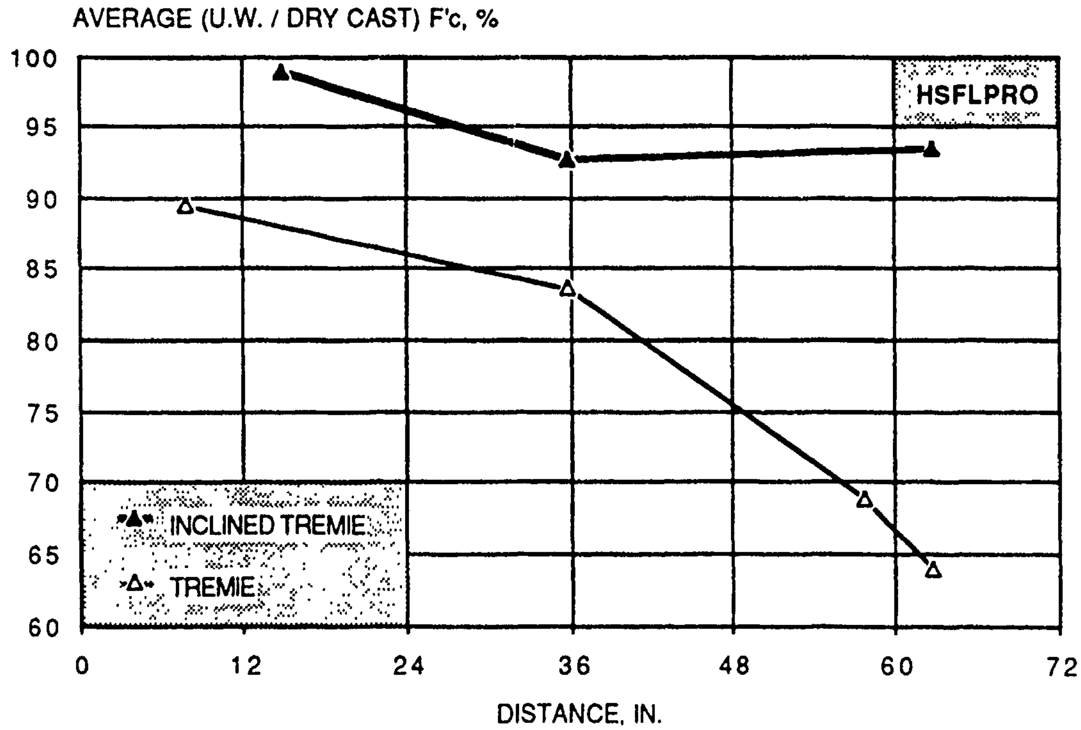


Fig. 44--Average Compressive Strengths along the HSFLPRO Slabs

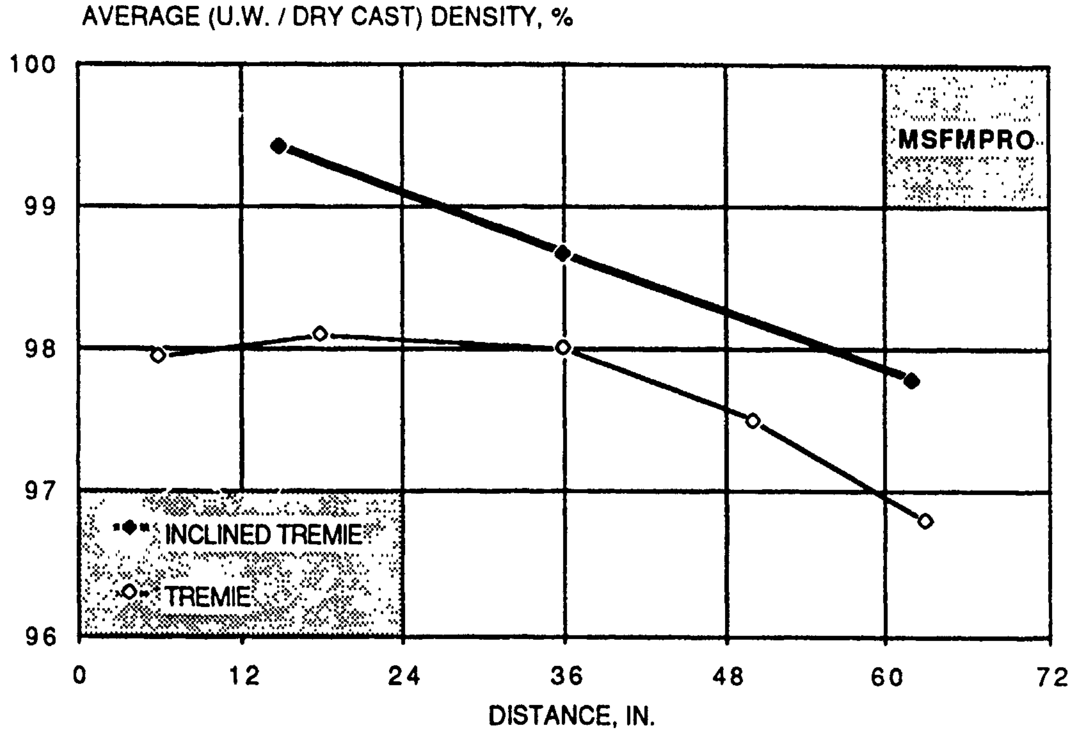


Fig. 45--Average Density Values along the MSFMPRO Slabs

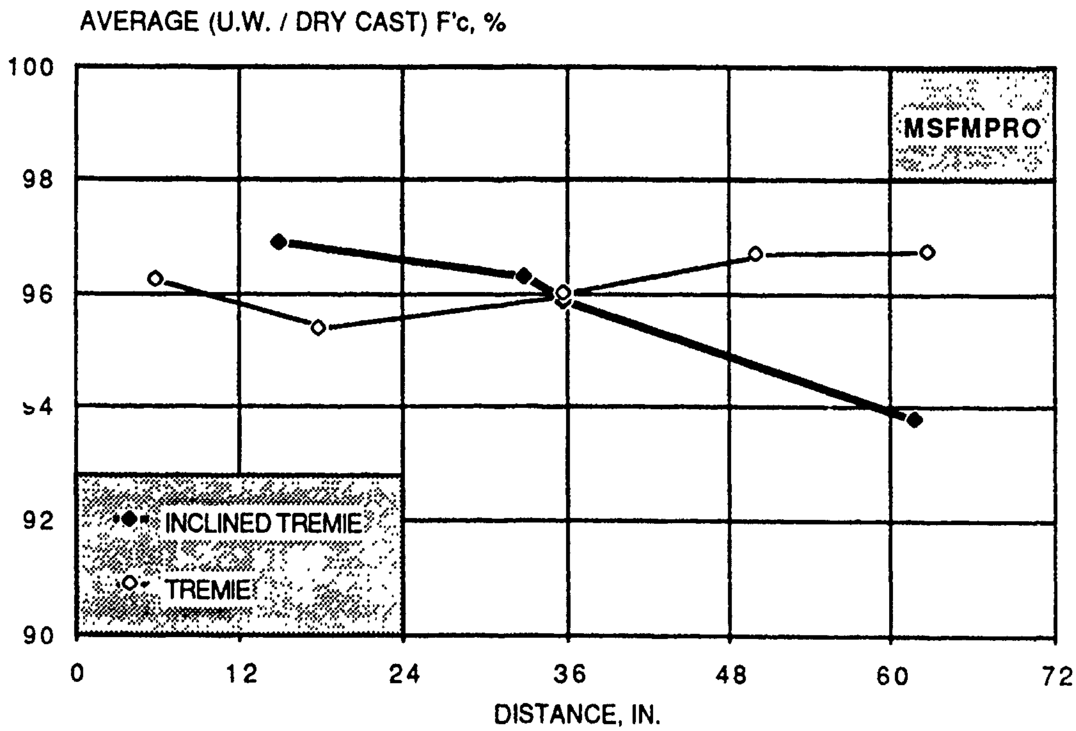


Fig. 46--Average Compressive Strengths along the MSFMPRO Slabs

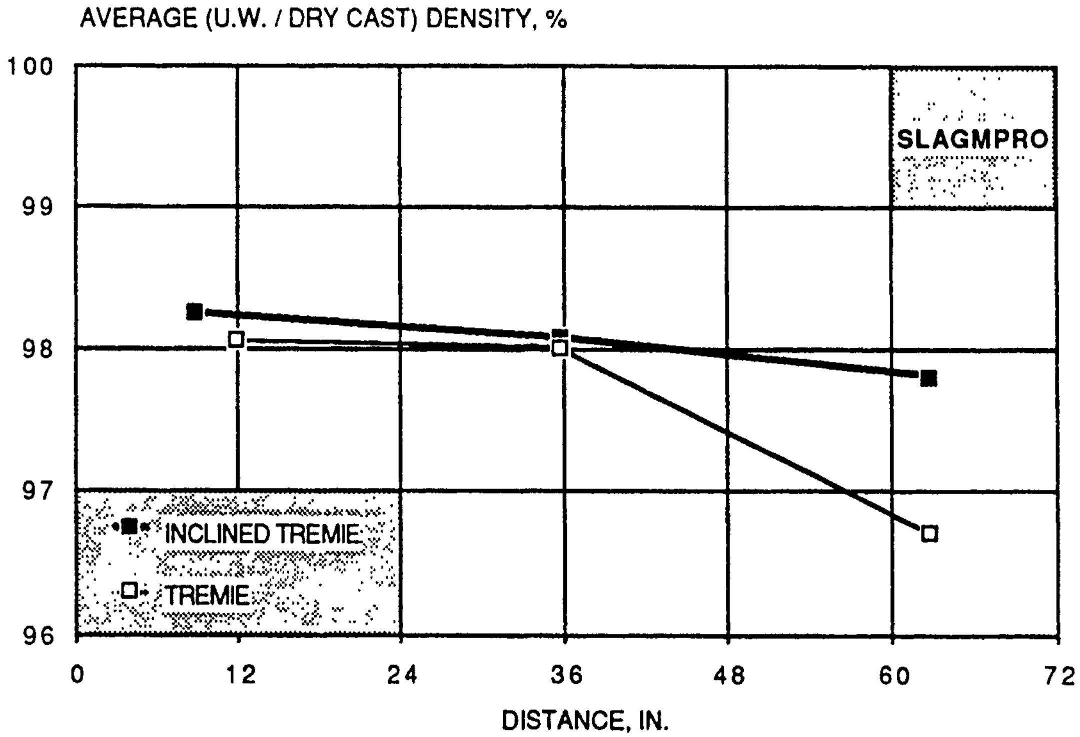


Fig. 47--Average Density Values along the SLAGMPRO Slabs

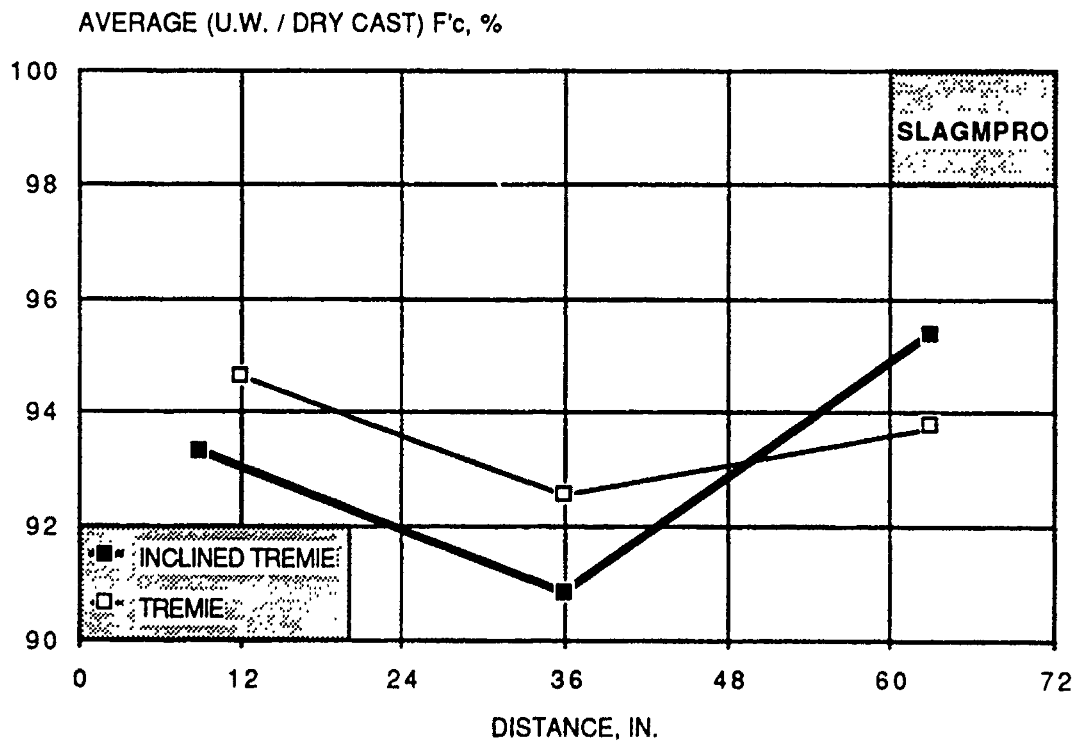


Fig. 48--Average Compressive Strengths along the SLAGMPRO Slabs

8.15 Field Repair of a Relatively Shallow Scour Hole

8.15.1 Scour Hole and Placement Pipe A field test was performed to fill a submerged hole with a repair concrete similar to the KELCO mixture (Chapter Seven) using the inclined tremie method. This was done to evaluate the performance of such material under field conditions and establish guidance for acceptable spacings between discharge points.

A trench measuring 16 ft in length was dug at the bottom of an excavated hole. Its width and depth varied from 2 to 2.5 ft, and its total volume was approximately 4.5 yd^3. The hole had jagged bottom and side walls that consisted of sandy materials topped with pea gravel. The top surface of the pit comprised of a flat concrete slab. A pipe measuring 9 ft in length and 8 in. in diameter was used to deliver the concrete from the side of the pit to the repair hole. The bottom end of the 45^0 inclined pipe was fixed 2.5 ft from the front side of the hole 9 in. above the base of the trench (Figure 49). The pit was then flooded with water until its top surface was one foot under water.

8.15.2 Mixing, Placement and Curing Unlike laboratory trials, the concrete was mixed inside a ready-mix truck. The cement, silica fume, fly ash and Kelco AWA contents were 600, 42, 30 and 1.5 lb/yd^3, respectively, and the W/CM was 0.47. The contents of sand and pea gravel were 1,300 and 1,550 lb/yd^3, respectively. HRWRA and AEA were added as 42 and 1.75 fl oz/100 lb of cementitious materials, respectively. The AWA was pre-mixed with most of the mixing water to obtain a 0.75 percent diluted solution. Thorough mixing of the polymer with water was achieved using a high-shear mixer.

A 7 yd^3 batch was prepared in a transit mixer. Gravel, cement, fly ash and 10 percent of the mixing water were first charged and mixed in the truck. Approximately 75 percent of the HRWRA was then mixed with the concrete before adding the pre-mixed AWA. Silica slurry fume was then charged in the truck along with 50 lbs of red dye to distinguished the repair material from the concrete on top of the pit. The sand was added

last after mixing the other materials since sand does not contribute to the needed shearing action during mixing. The last 25 percent of the HRWRA was administered at the jòb site. The concrete was placed 75 min. after the initial water addition at an ambient temperature of 90^0 F. The concrete flow value was 23.5 inches. Six 3 x 6 in. control cylinders were cast and consolidated above water to test the control density and f'_c values.

The concrete was transferred from the truck to a hopper attached at the top of the pipe. An inflatable plug was positioned at the mouth of the pipe to restrict the ingress of concrete at the begining of placement. The plug leaked and resulted in a 3.5 ft water column inside the pipe. Initially-charged concrete displaced this water upwards causing the material to intermix with water. The plug was then removed allowing the concrete to flow out of the pipe. Concrete was discharged continuously to fill the entire hole. The tube was then gently retrieved from the freshly-cast material. The remaining 2.5 yd^3 of concrete was dropped in a side pit filled with 2 ft of water to investigate the susceptibility of the concrete to segregation and water dilution when allowed to fall a large distance in water.

The pit was dewatered after one day to clean, inspect and photograph the repair area. Control cylinders were stripped and placed near the slab which was then flooded for 10 days. Thirteen cores measuring 12 in. long and 3 in. in diameter were drilled throughout the repair slab. They were stored along with control cylinders in lime-saturated water at 73 ± 3^0 F. The density and f'_c values were tested at 22 and 28 days, respectively.

8.15.3 Surface Appearance and Test Results Considering the rough and uneven boundaries of the repair hole, the concrete flowed nicely under water and filled the hole completely (Figure 50). The resultant surface slope of the slab was 1:35. The upper surface of the repair concrete was approximately 3.5 in. higher than that of the pit surface at the tremie location and 2 in. lower at the other end. As seen in Figure 50, excess concrete fell over the repair slab when the pipe was retrieved at the completion of the placement.

Figures 51 and 52 show the unit weight and f'_c values of the tested co es along the repair slab, respectively. The white and black data points refer to tested cores obtained from the top and bottom halves of the drilled cores, respectively. Core locations, descriptions, depths of segregated materials, laitance, density and strength values are summarized in Tables 39 and 40 (Appendix D). The front side of the hole near the discharge location was regarded as the origin, and the location of each core across the width of the hole was referred to as the distance from left or right edge of the hole.

In testing the relative density of concrete cores, two sets of results were observed: cores obtained ahead of the tremie location and cores taken near the discharge point. The first set of cores tested relative density values that ranged between 98.7 and 99.5 percent of the control density. The maximum increase in cut/uncut core densities of this first set of specimens was 0.55 percent, this value increased sharply in the last 4 ft of the slab. The relative densities of concrete cores taken near the tremie location ranged between 93.7 and 97 percent of control values. Unlike the other specimens, these cores contained air voids and segregated materials at their tops, which was reflected by the relatively high cut/uncut values. The well-defined drop in concrete density suggests that a disturbance zone was created near the discharge location. The average relative density of all 21 cores along the repair slabs was 98.1 percent of the control value.

The tested in-place f'_c results were scattered with consistently lower values measured near the tremie location. The maximum spread between the strength of any two cores was limited to 1,000 psi, which is not high considering the length, size and shape of the repaired hole. The f'_c values of 20 tested cores ranged between approximately 81 and 95 percent of the control strength. The average f'_c was 87.6 percent, or 6,380 psi.

Two cores were taken from the 10 in. slab that was formed by dropping concrete in 2 ft of water. The cores had 3.5 in. of segregated materials. The cut/uncut increase in density ranged between 4 and 4.5 percent. In-place average density and f'_c values of these cores were limited to 91 and 35 percent, respectively, of control concrete cast on land.

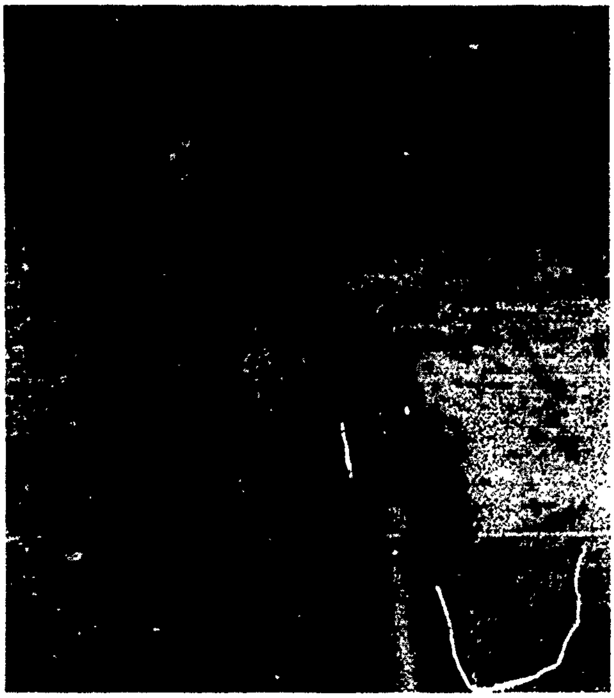


Fig. 49--Picture of Repair Hole with Inclined Tremie Pipe in Place

Fig. 50--Picture of Repair Slab Surface

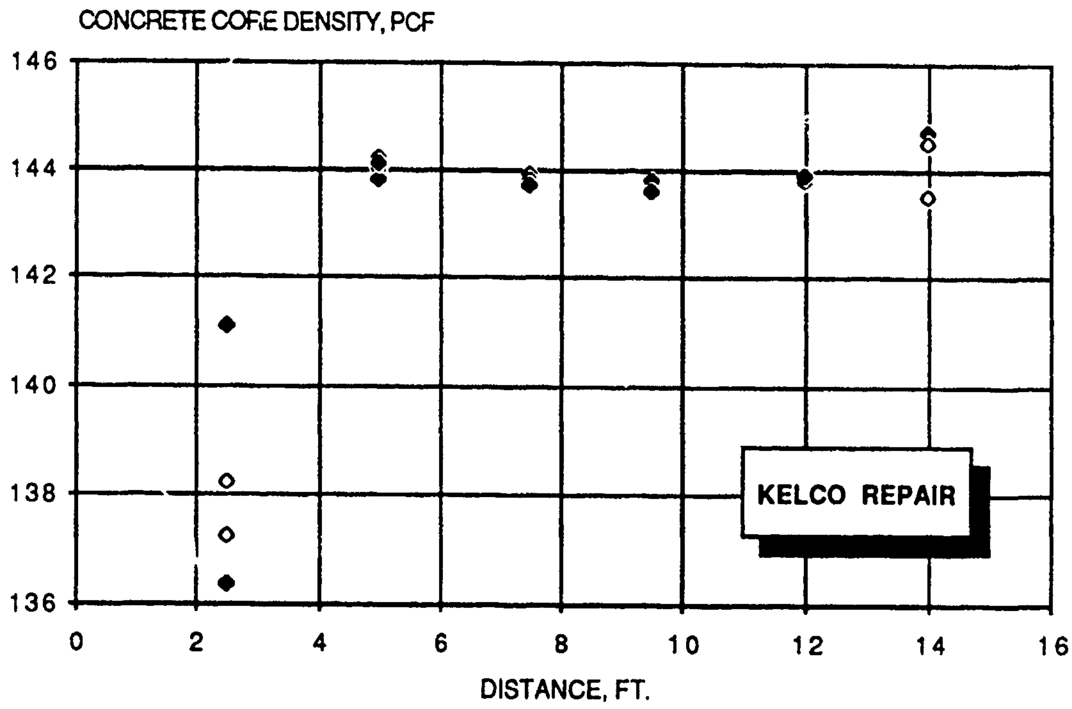


Fig. 51--Concrete Density along KELCO Repair Slab

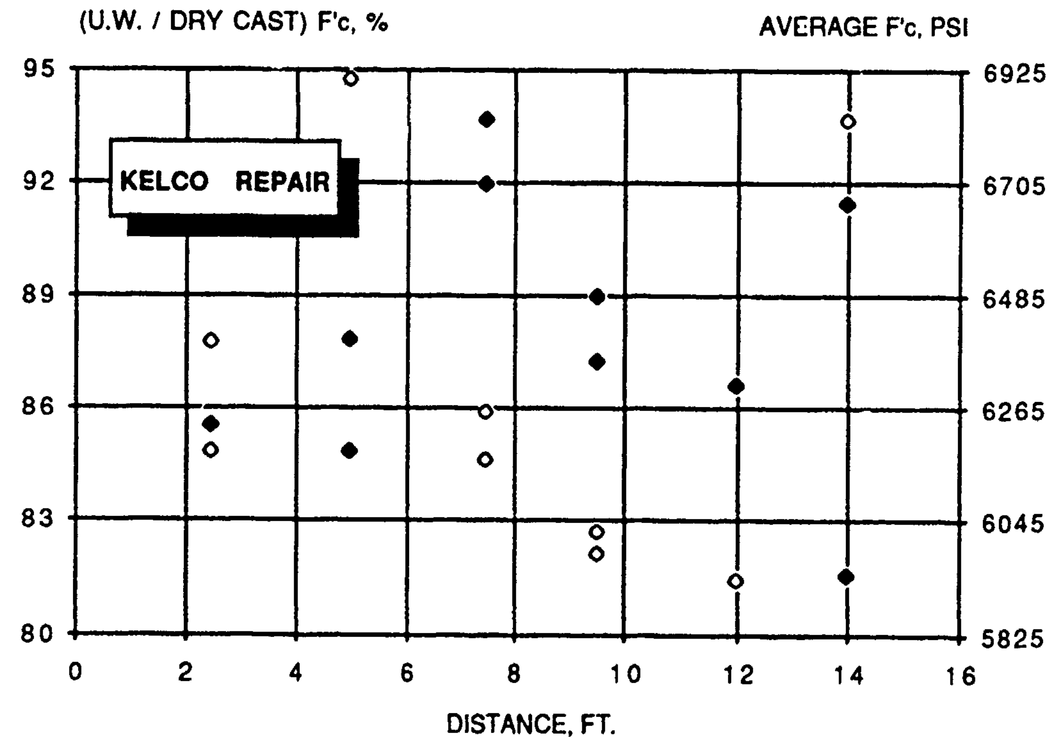


Fig. 52--Compressive Strength Results along KELCO Repair Slab

8.16 Summary and Conclusions

An extensive program was undertaken to evaluate concrete mixtures and identify simple and compatible placement procedures that are suitable for repairing small and relatively shallow (1 to 3 ft deep) scour holes under water. Appropriate concrete should resist water erosion since the limited thickness of such holes and the need to frequently move the placement device through water to repair neighboring holes can inhibit the maintenance of a continuous seal at the bottom of the casting device. Moreover, the concrete should be fluid and self-compacting since the small concrete volume delivered at any single location does not provide enough hydrostatic head to consolidate the concrete nor allow the placed concrete to remix in place.

Five concretes which were developed in the previous chapter were selected, four of which incorporated AWAs. The concrete was cast under water using a vertical tremie pipe as well as the proposed inclined tremie pipe (45^0). The placement box consisted of a 6 x 2.5 ft basin with jagged bottom to simulate a small scour hole. The base of the box was lined with a 5 in. thick concrete slab that was cast on land. Two 7 ft^3 lifts were cast in 2 ft of water. The bottom of the pipe was positioned 2 to 6 in. above underlying concrete at the start of each placement.

A total of eight slabs were cast under water and one above water. The latter was done to determine the quality reduction of concrete when cast under water. Surface profiles and flow patterns around boundary steps were observed. The in-place density and f'_c values were determined and compared to similar values of control specimens cast and consolidated on land.

As underwater placement began, a layer of colloidally-suspended fines was observed to propagate down the basin ahead of the concrete in the direction of the flow. The turbidity of this layer decreased with the increase in washout resistance of the concrete. Further disturbance was caused by the step boundary obstacles. The turbulence there

coupled with deposited fines at the toe of the first lift, resulted in noticeable local drops in concrete quality for some concretes.

In general, all four concretes incorporating AWAs exhibited favorable flow patterns, whereas the CONTROL mixture did not flow well under water and resulted in steep surface profiles and a large mound at the pipe location. The HSFLPRO-TREMIE slab had the flattest surface but resulted in the highest amount of laitance. Tremie-placed CONTROL and HSFLPRO concretes (whose washout resistance values were inferior to the other concretes) suffered maximum drops in density and f'_c of 5 and 47 percent, respectively, after flowing 4 to 5 ft in water.

The relatively gentle discharge of concrete through an inclined tremie pipe decreases the differential velocity between the freshly-placed concrete and surrounding water, thus reducing the intensity of water erosion and disturbance at step boundaries. The use of an inclined tremie pipe proved very effective with the HSFLPRO mixture which performed poorly when placed under water with a vertical tremie pipe. The resultant in-place density and f'_c were greatly improved, and the laitance development was immensely reduced. For example, the average in-place density and f'_c values of the slab cast with an incline tremie pipe were approximately 2 and 20 percent greater than those of the slab cast with a vertical tremie pipe.

SLAGMPRO and MSFMPRO concretes secured high in-place properties when cast under water with the conventional tremie method. Casting these concretes using the inclined tremie method resulted in slightly higher in-place densities (approximately one percent) and similar f'_c values. The movement of the inclined tremie pipe along the placement box resulted in relatively flat surfaces and low density losses. Although a seal was not maintained while moving the pipe in water, the in-place f'_c value of the SLAGMPRO-INCLINED TREMIE slab was comparable to that attained when concrete was cast with a fixed vertical pipe.

Despite the disturbance of concrete as it flowed in water and the presence of mud at some locations, concretes developed sound bonding under water. The average bond strength of the five tremie-cast concretes with the underlying base concrete ranged between 320 and 380 psi. Similarly, the average bond strength between two concrete lifts cast approximately one hour apart varied between 350 and 510 psi.

The surface profile of the dry-cast MSFMPRO-INCLINED TREMIE slab was similar to that of the underwater-placed one. The latter maintained lower in-place density values, especially as concrete spread away from the pipe. The relative in-place f'_c values of both slabs were similar. Neither slab had any laitance. The average bond strength at the interface of Lift A and Lift B for both slabs were identical. However, the dry-cast concrete developed 27 percent more bond strength with underlying base concrete than concrete cast in water.

Overall, the MSFMPRO mixture is considered to be the best performer with both vertical and inclined tremie placements, which is in agreement with the findings of the small-scale testing program presented in Chapter Seven. Average in-place density and f'_c values as high as 97.5 and 95.5 percent, respectively, of control values were secured with this concrete.

A large scale field experiment was carried out to cast the KELCO concrete under water using a 45^0 tremie pipe to repair a 16 x 2.5 x 2.5 ft hole submerged under 3.5 ft of water. The concrete was mixed thoroughly in a ready-mix truck. The concrete flowed well under water along the jagged and uneven hole surface of the repair hole and resulted in a final surface slope of 1:35. The average in-place relative density and f'_c of the repair concrete were approximately 98 and 88 percent, respectively, of control values. A well-defined disturbance zone was detected near the tremie location where sharp reductions in density were measured, and the concrete contained a large number of air voids.

In addition to repairing the trench, 2.5 yd^3 of concrete was dropped in 2 ft of water. The concrete did harden, however, its average in-place relative density and f'_c were limited to approximately 91 and 35 percent of control values, respectively.

Based on the above findings, the following conclusions can be drawn:

A. Measuring the DIN flow and slump values are not sufficient in assessing the spreadability of concrete under water. Instead, the underwater leveling test (section 7.6.3) should be used. As predicted with that test, the MSFMPRO and SLAGMPRO concretes achieved relatively gentle and acceptable surface profiles, while the CONTROL concrete did not spread well under water.

B. Concretes similar to the MSFMPRO, KELCO and SLAGMPRO mixtures (Chapter Seven) are believed to be suitable for repairing small and relatively shallow scour holes under water.

C. The placement of concrete with an inclined tremie pipe lowers the kinetic energy of the discharged material. The resultant reduced differential velocity at the interface between the concrete and the surrounding water can minimize water dilution, decrease laitance formation and secure higher in-place properties. Such improvements can be significant with marginal concrete mixtures (such as the HSFLPRO mix) which have moderate washout resistance values. If a sound concrete is employed for the repair, slightly higher in-place density can be provided when the concrete is placed with an inclined tremie pipe instead of a vertical pipe.

D. The horizontal movement of an inclined pipe under water to repair neighboring scour holes can be effective providing that the free-fall of concrete through water is minimized (6 to 12 inches).

E. The MSFMPRO concrete can be cast under water with either inclined or conventional tremie pipes to repair small and relatively shallow scour holes.

The concrete can secure in-place f'_c values greater than 8,000 psi after 100 days of curing. Similarly, relative density values higher than 98 percent of control concrete which is cast above water can be attained. Higher strengths may be provided by casting the HSFLPRO concrete with an inclined pipe. Such practice can result in an average f'_c value of 9,700 psi and an average relative density of 98 percent of control density.

F. Promising underwater-cast concretes can develop sound bond strengths to properly cleaned repair surfaces. Average bond strength values as high as 380 psi were measured. Similarly, consecutive concrete cast under water can bond well together (up to 510 psi) without the need to remove any settled materials from the lower lift surface. This can be done as long as the bottom concrete is still fresh in order to facilitate intermixing with the next lift and prevent the formation of cold joints.

G. The free-fall of concrete through water should be minimized even when the washout resistance of the concrete is superior. Reductions in density and f'_c values as high as 10 and 65 percent, respectively, were detected when a promising concrete was dropped 2 ft in water.

H. In repairing scour holes under water, the mouth of the inclined tremie pipe should be located as close as possible to the edge of the hole in order to limit the back flow of concrete behind the entry point where inferior concrete may be attained. In repairing long scour holes, inclined tremie pipes can be spaced as far as 15 ft apart.

CHAPTER NINE

CONCRETES FOR CASTING REINFORCED SLABS OR FILLING DEEP SCOUR HOLES UNDERWATER

9.0 Objective

Casting reinforced concrete slabs under water without consolidation presents a great challenge in securing structural quality concrete that can flow readily around reinforcing bars and yield flat and smooth surfaces. Similar problems emerge when large and deep scour holes (more than 3 ft) need to be filled under water with sound concrete that is capable of spreading away from the discharge location and forming flat surfaces. Such concrete should have the following properties:

A. Superior self-leveling and self-compacting abilities to secure flat surfaces.

B. Good workability retention to avoid plugging of placement devices.

C. Adequate cohesiveness to reduce segregation and bleeding without impairing flowability.

D. Satisfactory washout resistance to minimize water erosion caused by turbulence as concrete flows past reinforcing steel, dowel bars, structural columns and around scour hole boundaries.

E. Proper strength development and bonding to reinforcing steel and surrounding damaged surfaces.

The experimental work presented in this chapter was divided into two phases. The first aimed at developing very fluid concretes and evaluating their suitabilities for casting moderately congested reinforced beams under water. Two concretes with similar mix proportions but different fluidity levels were used for casting these beams in the laboratory.

The experiments were carried out to observe the surface profiles and laitance developments and to determine the resultant in-place mechanical properties for each concrete.

In the second phase, a large scale field placement was carried out to cast two 10 yd^3 concrete slabs under water. The slabs were cast using two concretes of similar mix proportions, but which contained different types of AWAs. The experimental program was undertaken to evaluate the surface appearance and measure the in-place mechanical properties. Other important parameters, such as proper spacing between discharge locations and the effect of interrupting the discharge of concrete were determined. The proper mixing sequence of concrete and the ease of cleaning ready-mix trucks, tools and equipment were evaluated.

9.1 Development of Concrete Mixtures

Concrete-making materials and additives were similar to those described in section 7.1. Several trial mixtures were prepared to obtain highly fluid concretes that can achieve good balance between the above desired characteristics. The mixtures used were similar to the KELCO and MSFMMB concretes (Chapter Seven), except their fluidity levels were enhanced by reducing the concentrations of AWAs and slightly increasing the amounts of HRWRAs or W/CMs. The enhanced fluidity level increased the susceptibility of the concrete to segregation and water erosion. For example, reducing the AWA dosage of the KELCO mixture without changing the W/CM increased the initial flow value from 19.5 to 27.5 in., but also resulted in increasing the washout weight loss from 1.5 to 10 percent after three test drops in water.

Table 12 summarizes the mix proportions and basic properties of the four concrete mixtures used in this study. The first three concretes used the Kelco AWA, while the last one used the Master Builders AWA. The KT-1 and KT-2 concretes were employed for casting two reinforced beams in the laboratory, whereas the K-FIELD and MB-FIELD mixtures were employed for casting two large slabs in the field.

Table 12. Concrete Mix Proportions and Properties

MIXTURE	KT-1	KT-2	K-FIELD	MB-FIELD
CEMENT, PCY	610	600	600	600
SILICA FUME, PCY	43	42	42	42
FLY ASH, PCY	31	30	30	30
TOTAL CM, PCY	684	672	672	672
W/CM	0.46	0.46	0.46	0.48
SAND, PCY	1340	1320	1320	1340
PEA GRAVEL, PCY	1595	1565	1565	1590
HRWRA, FL OZ/100# CM	48	50	40	50
AWA TYPE	KELCO HYDRATED	KELCO HYDRATED	KELCO HYDRATED	M. BUILD. POWDER
AWA, % CM	0.25	0.1	0.1	0.3
DE-AIR, % CM	0	0	0	0.075
AEA, FL OZ/100# CM	1.25	1.75	1.75	0
CaCl2, % CM	0	0	0	0.75
SLUMP, IN.	10.25	11	- -	- -
FLOW, IN.	23	28	27.5	28.5
UNIT WEIGHT, PCF	146.7	146.7	- -	- -
AIR VOLUME, %	2	1.5	- -	- -
CURING IN WATER, DAYS	4	7	10	6
IN LIME BATH, DAYS	5 - 28	8 - 24	11 - 29	7 - 29
F'c, PSI	7020	6700	8100	7100

9.2 Phase I - Underwater Casting of Reinforced Concrete Beams

9.2.1 KT-1 Placement Box and Casting Pipe The KT-1 concrete was cast in a 9 x 1.5 ft wooden box lined with plastic. A pre-fabricated cage consisting of top and bottom horizontal steel bars (No. 6) spanning in both directions, as well as some vertical bars, was positioned in the box with 2 in. bottom and side clearances. The bars were spaced approximately 12 in. apart (Figure 86, Appendix E).

A pipe measuring 6 in. in diameter was used to cast the concrete under water. As shown in Figure 53, the pipe was inclined 42^0 from vertical. Its lower center was positioned 16 in. from the front of the basin, 8 in. above the base. A neoprene-lined wooden plate was attached to the bottom of the pipe to restrict the ingress of materials before the pipe is completely filled with concrete. The basin was filled with 2 ft of water.

9.2.2 KT-2 Placement Box and Casting Pipe The KT-2 concrete was placed in a wooden box measuring 11 x 2 feet. The box was lined with plastic, and a reinforcing steel cage similar to that described in the previous section was positioned inside it.

The same tremie pipe employed for casting the KT-1 slab was used in this placement. The pipe was fixed at a 45^0 with its lower end center located 20 in. from the front of the box and 10 in. above its bottom (Figure 55). A plug similar to the one described in the previous section was attached to the bottom of the pipe to restrict the ingress of materials before the pipe is completely filled with concrete. The placement box was then flooded with 2 ft of water.

9.2.3 Mixing and Casting the KT-1 Beam The KT-1 concrete was prepared in two 8 ft^3 batches that were mixed separately into an open-pan mixer. The AWA was mixed with approximately one third of the mixing water and was added last to the wet concrete. Both batches were prepared before the casting began.

The first batch was directly poured from a bottom-dumping bucket that was mounted over a hopper attached to the top of the pipe (Figure 87, Appendix E). Concrete initially discharged in the pipe was diluted by the 2 ft water column that was inside the pipe at the start of the placement. The concrete displaced that water, then the end plug was quickly removed, and the concrete was continuously charged until the bucket was empty. Concrete rushed out of the pipe and flowed readily along the placement box.

The second 8 ft^3 of concrete was stored in three wheelbarrows that were positioned directly behind the hopper (Figure 87, Appendix E). At the beginning of the second lift placement, the bottom of the pipe was already submerged in the first concrete lift. Therefore, the second concrete batch proceeded slowly out of the pipe, and some concrete was observed to propagate upward near the discharge location before flowing over the already-cast material. The pipe had to be retrieved slowly out of the concrete to complete

the placement. Six 3 x 6 in. control cylinders were cast and consolidated on land to measure the density and f'_c of the concrete.

9.2.4 Mixing and Casting the KT-2 Beam All of the concrete-making materials, except the silica fume, HRWRA and AWA, were mixed in a transit mixer. The AWA was blended with the HRWRA before charging the solution into the truck. Silica fume powder was added last to the wet concrete, and the concrete was mixed in the truck for an additional 5 minutes. The concrete contained balls of dry materials (mainly cementitious materials and sand) which did not disperse into the wet ingredients during mixing.

The concrete was transferred directly from the truck into the hopper. Because of the large capacity of the truck, the 1.75 yd^3 concrete was charged continuously in the hopper. The concrete flowed readily out of the pipe and spread well along the beam. The pipe was fixed during casting and was removed gently from the concrete at the completion of the placement. Eight 3 x 6 in. cylinders were prepared on land to measure the properties of the control concrete.

9.2.5 Coring and Testing Sounding data was collected at the completion of the underwater placement to establish surface profiles. The KT-1 and KT-2 beams, along with the control cylinders, were kept under water for 4 and 7 days, respectively. The beams were then stripped, and a total of 13 and 22 cores measuring 3 in. in diameter were obtained from the KT-1 and KT-2 beams, respectively (Figures 88 and 89, Appendix E). The left-front corner of each beam was considered to be its origin, with the X and Y coordinates of the cores being the transverse and longitudinal distances from the origin, respectively. The cores were examined and photographed, then transferred along with the control cylinders to a lime-saturated water bath at 73 $\pm$ 3^0 F.

The density and f'_c values of the KT-1 and KT-2 concrete specimens were tested at approximately 28 and 24 days of age, respectively. The unit weight values were

determined prior to and after cutting the core ends to remove loose materials. The cut cores were then tested in compression following the procedures outlined in section 8.1.6.

9.2.6 Appearance and Test Results of KT-1 Beam The surface profile of the KT-1 beam, along with the steel cage and discharge locations, are shown in Figure 53. Despite the high flow and slump values (23 and 10.25 in., respectively) of the KT-1 concrete, it did not flow well in the box and resulted in steep surfaces.

The high internal shear resistance of the fresh concrete, caused by the high dose of AWA, is partially responsible for the low spreadability of the concrete under water. However, the primary reason for the resultant steep surface profiles is believed to be due to the interruption of the concrete flow which occurred between the first and second batch placements. At the beginning of the second lift placement, the limited concrete head inside the short pipe was not sufficient to readily overcome the passive pressure at the mouth of the submerged pipe, the external friction caused by the steel cage, and the internal shear resistance of the concrete. As a result, the concrete from the second placement seemed to flow mostly in a vertical fashion at the tremie location and propagate over the first lift.

No mud was collected anywhere from the surface of the beam. The average relative density and f'_c values along the KT-1 beam are plotted in Figure 54. The unit weight and f'_c measurements of all of the individual cores are summarized in Figures 90 and 91, respectively (Appendix E). The white and black circles in these plots refer to specimens tested from the top and bottom sections of the extracted cores, respectively.

The in-place concrete density did not vary much along the beam. The average relative density of all tested cores was 98.7 percent of the control value. The average f'_c values decreased as the concrete spread away from the discharge location. The strength loss was especially high toward the end of the slab. The average in-place f'_c near the discharge location was 6,645 psi, which was approximately 1,000 psi greater than that at the opposite side of the beam.

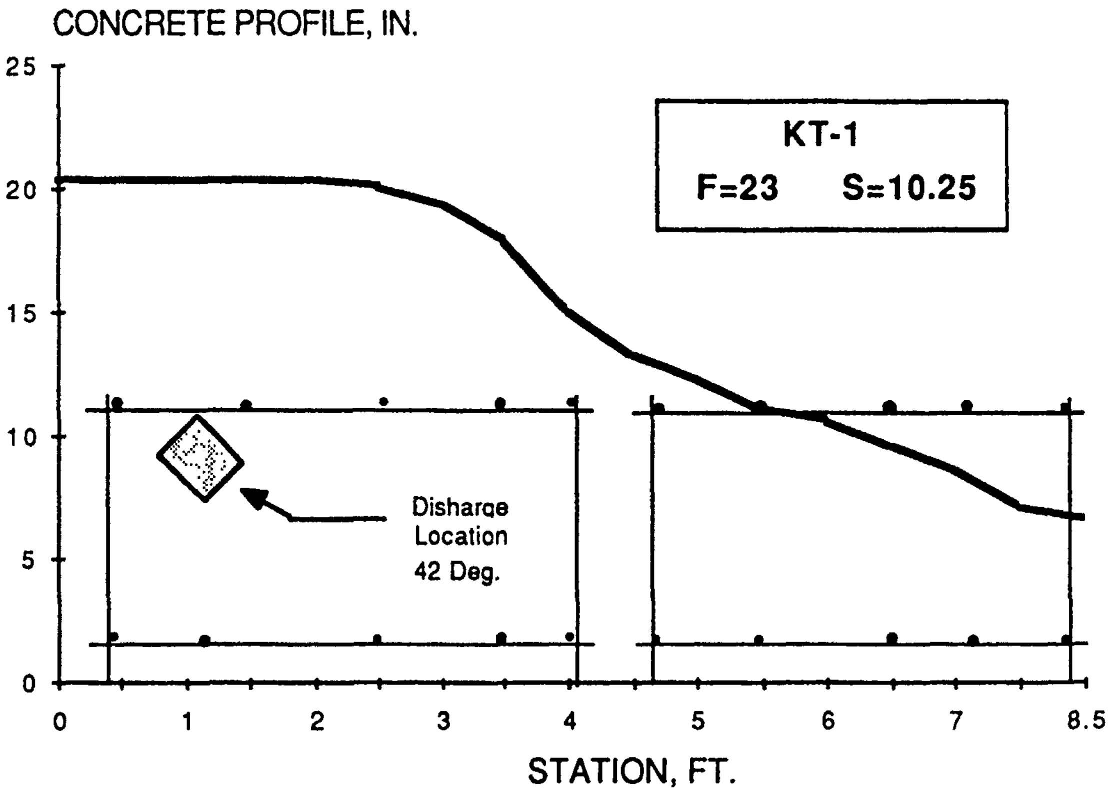


Fig.53--Surface Profile of the KT-1 Beam

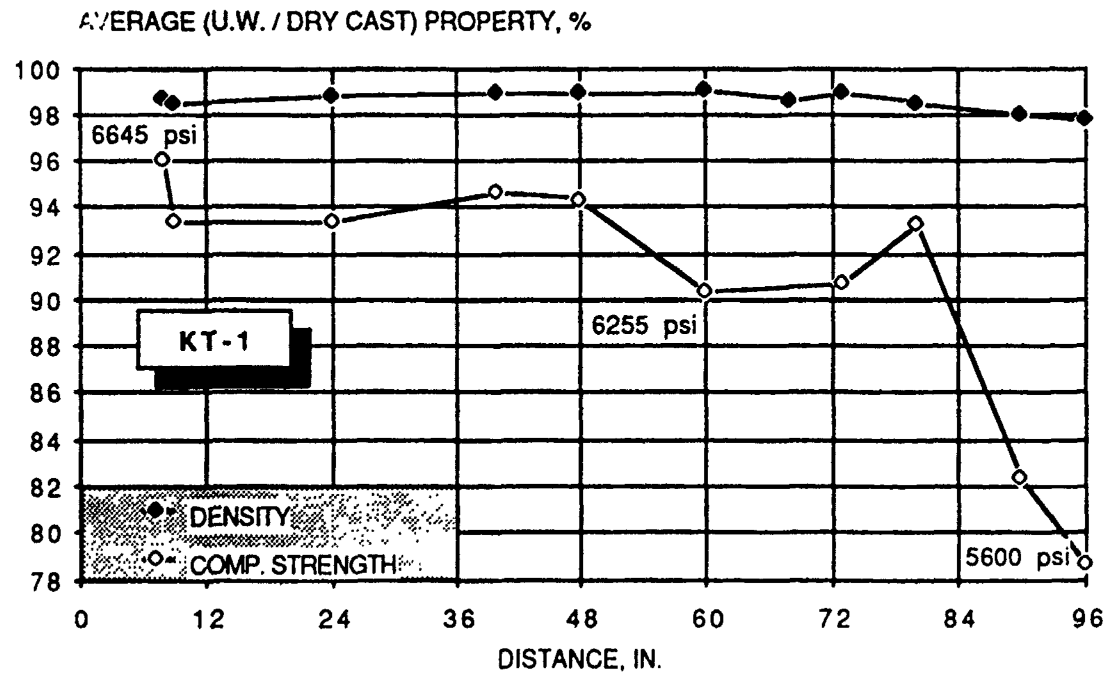


Fig. 54--Average Density and Compressive Strength Values along the KT-1 Beam

9.2.7 Appearance and Test Results of KT-2 Beam Figure 55 shows the position of the steel cage, discharge location and surface profile of the KT-2 beam. Unlike the first mixture, the KT-2 concrete had a lower dosage of AWA and a higher fluidity value (28 in. flow instead of 23 in. flow). Therefore, the reduced internal shear resistance of the concrete, coupled with the continuous feeding from the transit mixer allowed the concrete to spread readily around the steel cage resulting in flat and smooth surfaces. The maximum difference in concrete depths at both ends of the beam was 1.5 in., thus yielding a 1:90 surface slope.

The KT-2 concrete was more susceptible to water erosion than the KT-1 mixture because of its lower AWA content. As a result, the concrete suffered more intermixing with water than the KT-1 mixture, and a thin layer of laitance was deposited at the top surface. The thickness of this layer was limited to 0.15 inches. However, the increase in cut/uncut core density varied from 0 to 2.9 percent, with the higher readings obtained from the cores taken from the end of the beam.

The average relative density and f'_c values along the KT-2 beam are plotted in Figure 56. The unit weight and f'_c values of all of the tested cores are presented in Figures 92 and 93 and Tables 41 and 42 (Appendix E). The in-place density values of the concrete were high throughout the slab. The relative density of 42 tested specimens varied from 98.6 to 100.5 percent of the control concrete cast above water, and the average density was 99.8 percent. Similarly, the in-place f'_c of 38 of the cores ranged between 84 and 104 percent of the control strength. In-place f'_c values exhibited an 8 percent drop in the first 2.5 ft of the beam but were nearly constant thereafter. The average f'_c at the front and the far side of the beam were 6,860 and 6,070 psi, respectively (or only 790 psi reduction in f'_c over the 11 ft beam).

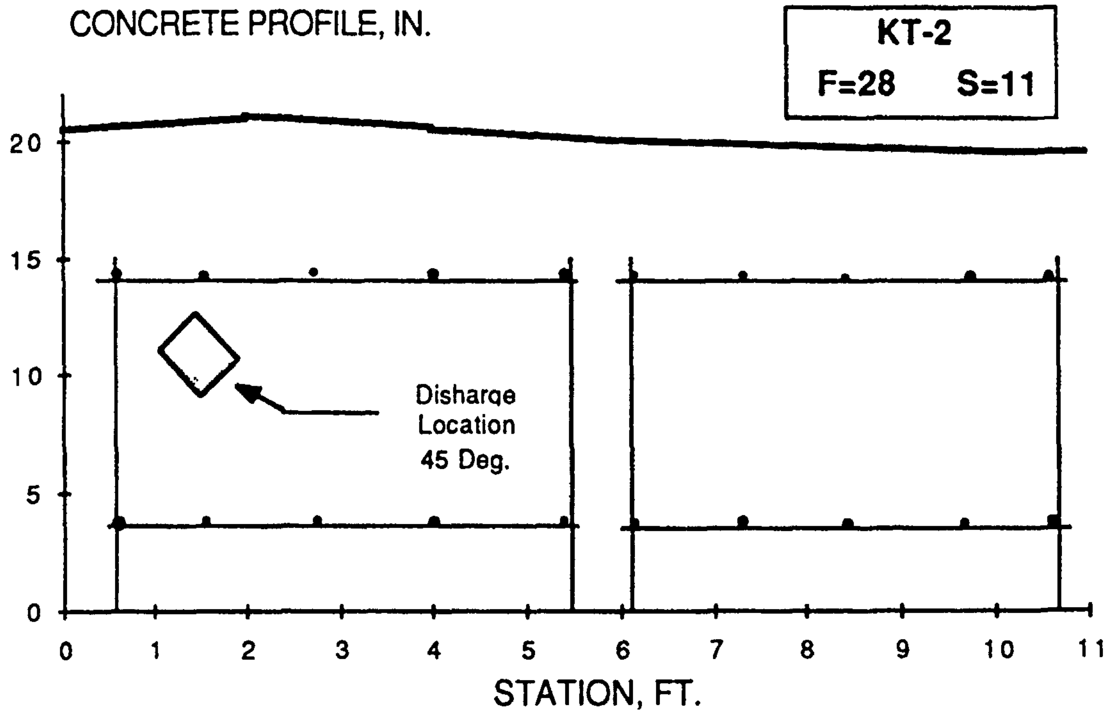


Fig. 55--Surface Profile of the KT-2 Beam

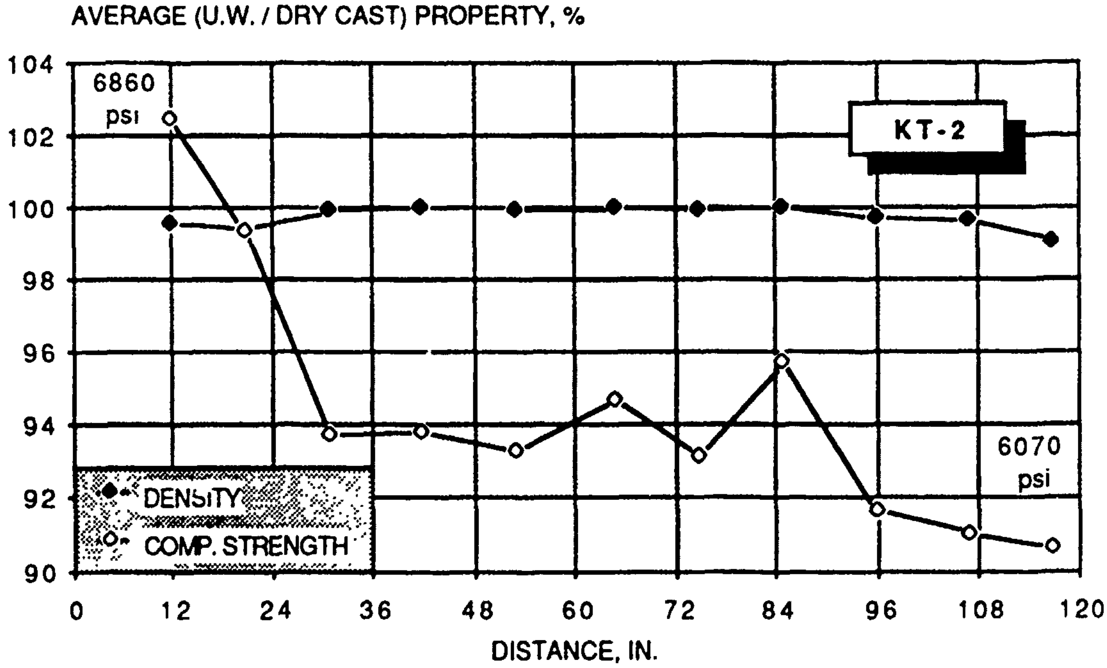


Fig. 56--Average Density and Compressive Strength Values along the KT-2 Beam

9.3 Phase II - Underwater Casting of Large Flat Slabs

9.3.1 Hole Description A 22 x 22 x 6 ft pit was dug at a local aggregate producing plant. The bottom of the pit was covered with a 6 in. blanket of gravel. A 16 in. gravel burn was provided along the middle of the pit to divide its bottom into two sections each measuring approximately 22 x 10 x 1.3 ft (Figure 94, Appendix E). The holes were filled with the K-FIELD and MB-FIELD concretes (Table 12) under water. The origins of these basins were considered to be their front-left and front-right corners, respectively, with the X and Y axes pointing in the short and long directions of the basins, respectively.

Two wide-flange steel columns were positioned approximately 18.5 ft from the front side of each basin. The columns were spaced 3 ft apart and were firmly anchored in the ground with their tops sticking 2 to 2.5 ft in the air. Three No. 3 steel bars measuring 5 ft in length were attached to the front of the columns approximately 18 ft from the origin. The bars were spaced approximately 4, 8 and 12 in. above the ground (Figure 95, Appendix E). This was done in order to observe the flowability of the concrete around obstacles and measure the extent of laitance development and strength deterioration caused by the disturbance created by the closely-spaced bars.

9.3.2 Placement Pipe A 9 ft long and 8 in. diameter pipe was used for delivering concrete to the basin from a transit-truck mixer located at the side of the pit. The mouth of the 45^0 pipe was fixed 6 ft from the front side of the hole and 9 in. above its base. A hopper was attached to the top of the pipe to facilitate the transferral of concrete into the pipe (Figure 96, Appendix E). A neoprene-lined wooden block with a backup stub was attached to the bottom of the pipe (Figure 97, Appendix E). Figure 98 (Appendix E) shows one completed basin in the dry with a couple of extra obstacles that were positioned behind the discharge location. The bottom of the pit was leveled and surveyed before it was flooded with 5 ft of water.

9.3.3 Mixing and Placement of Concrete Each concrete was prepared in a 10 yd^3 batch and mixed in a ready-mix truck. The adopted mixing sequence was different than those previously used (sections 8.15.2 and 9.2.4). The pea gravel was first mixed with silica fume slurry inside the truck to coat the aggregate with silica fume in order to enhance the transition zone between the aggregate and the hardened cement paste. The cement and fly ash were then charged along with the sand and approximately one third of the mixing water. The concrete was mixed for 3 min. before adding the HRWRA. For the K-FIELD concrete, the AEA was also introduced at this stage. For the MB-FIELD concrete, diluted $CaCl_2$ was then added.

The Kelco AWA was hydrated with water to make a 0.67 percent concentrated solution using a high-shear mixer. The pre-hydrated slurry was pumped last into the truck. For the MB-FIELD, the Master Builders AWA was added last in the form of a powder followed by the de-airing additive.

The casting of concrete under water began approximately 75 min. after the start of mixing at an approximate ambient temperature of 90^0 F. The initial flow values of the K-FIELD and MB-FIELD concretes were 27.5 and 28.5 in., respectively. Unfortunately, because of the adopted sequence of charging the concrete making-materials and the relatively low mixing action provided by the ready-mix truck lumps containing dry cementitious materials and sand (as large as one foot in diameter) were obtained along with the fluid concrete.

The concrete was transferred directly from the truck into the hopper (Figure 99, Appendix E). The plug at the nose of the pipe did not prevent water from seeping inside the tremie tube. Therefore, concrete initially charged into the pipe displaced the 5 ft column of water upward resulting in some intermixing with water. Once the pipe was completely filled with concrete, the plug was quickly removed allowing the concrete to flow out. The concrete was continuously fed. The flow was occasionally interrupted to remove large lumps from the truck chute or from the hopper. Occasionally, relatively

small lumps of dry materials flowed into the tremie tube and had to be pushed through the pipe with a long steel rod. At the completion of casting, the pipe was gently retrieved from the freshly-cast material.

Approximately 1 yd^3 of the MB-FIELD concrete was allowed to fall from the truck 2 ft in air and a distance of 3 ft through water into a side pit. This was carried out to investigate the susceptibility of this fluid concrete to segregation and water erosion when allowed to fall a large distance through water.

9.3.4 Coring, Curing and Testing The pit was dewatered after one day to clean, inspect, photograph and survey the two slabs. The concrete surface was found to be covered with approximately 6 in. of mud which resulted mainly from the eroded side walls of the pit. The mud was removed, and the concrete surface was flushed with water. Control cylinders were stripped and placed near the slab which was then flooded for 10 more days. Fifteen cores measuring 12 in. in length and 3 in. in diameter were obtained from each slab. The cores and control cylinders cast above water were stored in lime-saturated water at 73 ± 3^0 F. The density and f'_c values were tested between 27 and 29 days of age.

9.3.5 Surface Appearance Both concretes completely filled the holes and resulted in smooth and flat surfaces. Figure 57 shows a picture of the dewatered pit with cleaned slab surfaces. The left slab seen in Figure 57 was the K-FIELD slab, and the right one was the MB-FIELD slab. The narrow slab in the middle was that of the repaired hole that was described in section 8.15. The depths of the K-FIELD and MB-FIELD slabs ranged between 14.5 and 16.5 in., with average thicknesses of 15.75 and 15 in., respectively. The average surface slopes of both slabs were 1:190, or a drop of one inch every 16 feet. The concrete flowed readily around the steel columns and past the horizontal reinforcing bars spanning between them without forming any mounds at the vicinity of these obstacles (Figure 58).

Fig. 57--Photograph of the Field-cast Slabs

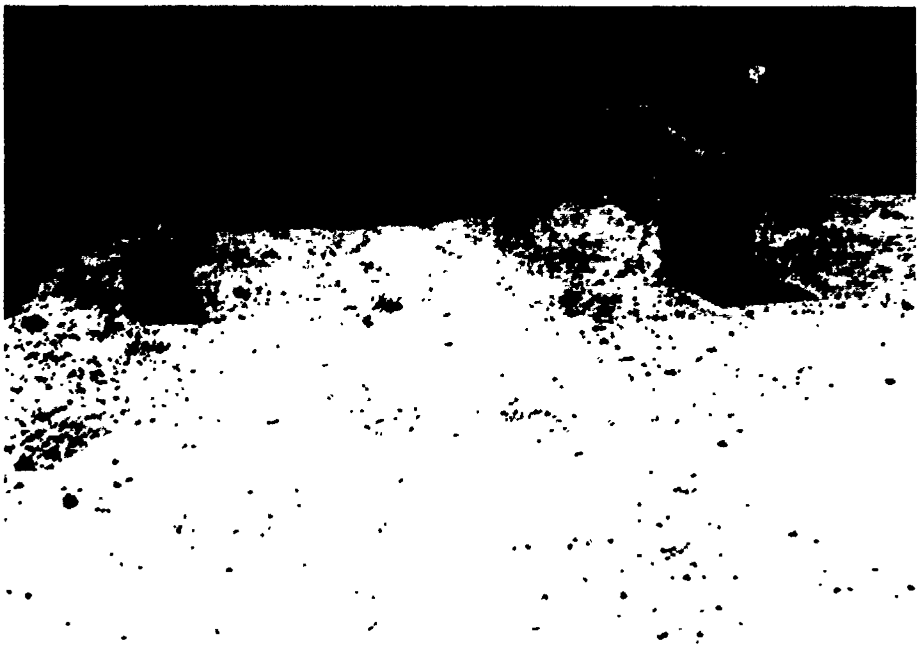


Fig. 58--Picture Showing Concrete Near the Steel Beams

9.3.6 Test Results of the K-FIELD Slab The coordinates of the tested cores, their descriptions, measured density and f'_c values are summarized in Tables 43 and 44 (Appendix E). Figures 59 and 60 show the density and f'_c values of the tested K-FIELD cores along the slab, respectively. The legend of the data points used in these graphs are the same as those described in section 9.2.6.

In general, the in-place concrete quality was high everywhere except behind the discharge location and beyond the steel columns. The properties of the cores taken from the top of the slab were lower than those which were obtained from the bottom of the slab. In-place relative density values along the slab ranged from 97.7 to 99.8 percent of the control concrete density. The f'_c of 17 cores taken between the discharge point and the steel columns ranged from 82.5 to 102.2 percent of the control value. The average in-place f'_c was approximately 7,700 psi, or 400 psi less than the control strength.

The density and f'_c values of concrete cores taken from behind the discharge point were considerably inferior to those measured directly ahead of the pipe. It is believed that the back flow of concrete behind the inclined tremie pipe increased the deposit of diluted cement paste in that location. Moreover, the retrieval of the pipe from the concrete at the completion of the casting is also believed to have contributed to the disturbance of the concrete there.

Sharp drops in concrete quality were also obtained beyond the steel columns. The funne'ling of the concrete through the closely-spaced horizontal bars resulted in a high amount of turbulence which greatly increased the intermixing of concrete with water and resulted in laitance and segregation. Strength values as low as 51 percent of the control values were obtained in that location. Cores taken 2 ft behind the horizontal steel bars had depths of laitance and segregated materials of 0.5 and 3 5 in., respectively. The tested cores had large increases in cut/uncut densities which ranged between 2.1 and 4.2 percent.

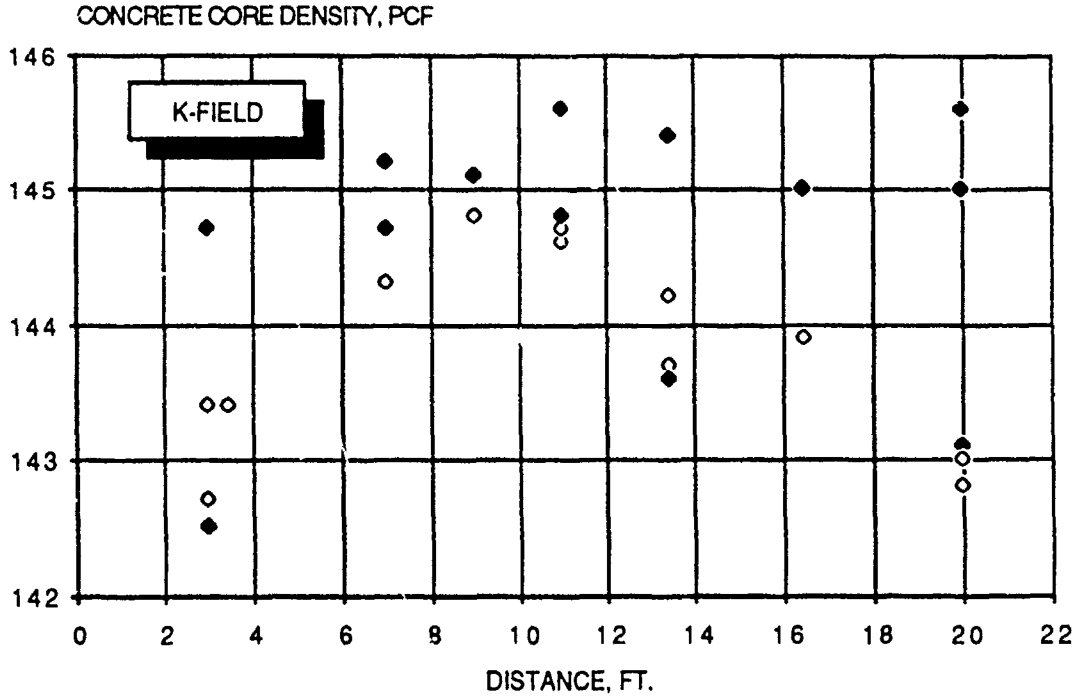


Fig. 59--Density Values along the K-FIELD Slab

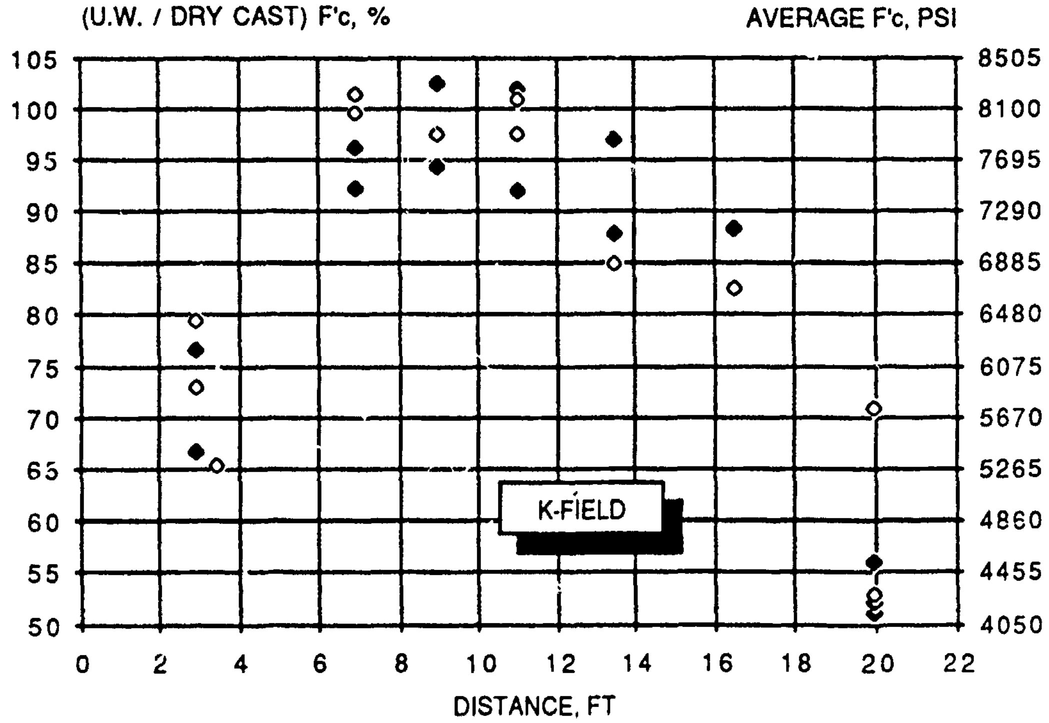


Fig. 60--Compressive Strength Values along the K-FIELD Slab

9.3.7 Test Results of the MB-FIELD Slab Tables 45 and 46 (Appendix E) summarize the density and f'_c results of the MB-FIELD cores, respectively, along with their coordinates and descriptions, and Figures 61 and 62 plot these values. A considerable amount of air bubbles were found in the cores, especially for specimens taken directly ahead of the discharge location. The quality of concrete from the bottom part of the slab was higher than the quality of concrete from the top part of the slab.

Although the tested density and f'_c results were scattered, their average values decreased gradually as concrete spread away from the discharge point. The maximum spread between f'_c values of any two cores was limited to 900 psi, which is low considering the size of the slab and the condition of the casting. Relative in-place concrete densities ranged between 95.5 and 102.4 percent of the control concrete which was cast above water, and the average density of 23 tested cores was 98.6 percent. The f'_c of the cores varied between 88.6 and 100.9 percent of control strength. The average f'_c was 94.1 percent, or approximately 6,700 psi which was only 400 psi less than the control f'_c.

The density values of cores taken from behind the discharge location were slightly lower than those obtained directly ahead of it. The increases in cut/uncut densities of such cores varied between 2.4 and 4.8 percent, and the depth of laitance in that location was one inch. Unlike the K-FIELD slab, cores obtained from beyond the steel beams did not show an appreciable reduction in quality. This might have been because the steel bars of the MB-FIELD slab spanning between the columns were not connected to the side wall of the pit at one side, as was the case with the K-FIELD slab. Hence, concrete could have flowed from either side of the columns to intermix with the funnelled material, thus improving the quality of the concrete there.

The 1 yd^3 of concrete dropped in 3 ft of water segregated completely indicating that the concrete must not be allowed to fall freely in water. This is important since the concrete was proportioned to have relatively low resistance to water erosion in order to achieve superior fluidity and was intended to be discharged within freshly-cast concrete.

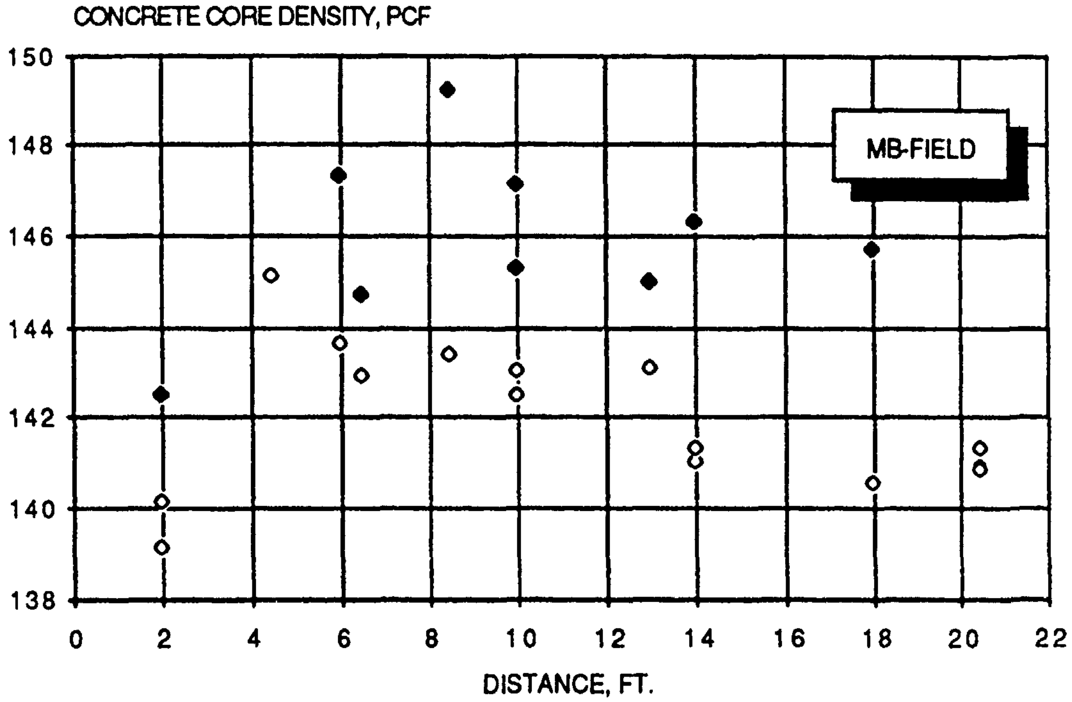


Fig. 61--Density Values along the MB-FIELD Slab

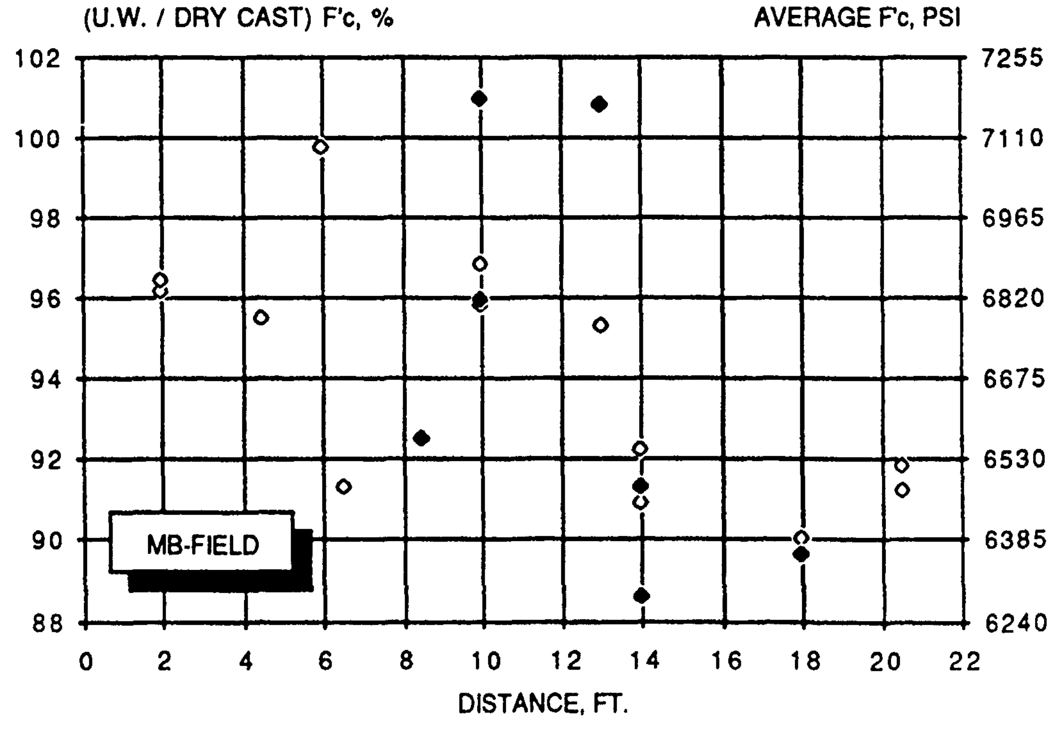


Fig. 62--Compressive Strength Values along the MB-FIELD Slab

9.4 Summary and Conclusions

Fluid concretes suitable for the underwater placement of reinforced beams and for the repair of large and deep scour holes (more than 3 ft) were developed. Concretes were proportioned to self-level and self-compact and develop moderate washout resistance values. They contained high concentrations of HRWRAs and low doses of AWAs. The high fluidity of these concretes is believed to enable them to remix and consolidate in-place once cast under water, thus compensating for some of the deterioration in quality caused by the lack of high washout resistance.

Two reinforced beams were cast in 2 ft of water using the proven inclined tremie method. The reinforcing cage consisted of top and bottom bars (No. 6) spaced 12 in. apart and spanning in two directions, as well as some vertical bars. Two concretes with different consistencies were employed. The KT-1 concrete incorporated a high concentration of AWA and had a 23 in. flow value. Its relatively high cohesiveness, coupled with the interrupted concrete placement resulted in steep surface profiles.

The second mixture (KT-2) had a low dose of AWA and a 28 in. flow value. The bottom of a 45^0 pipe used in casting a 20 in. deep KT-2 beam was positioned approximately 10 in. from the bottom of the beam. The high fluidity level of the KT-2 concrete and the continuous feeding of the concrete from a ready-mix truck enabled the concrete to overcome the passive pressure at the bottom of the pipe and the friction caused by the reinforcing cage. The concrete flowed well around the steel bars and secured smooth surfaces (1:90 slope). The average in-place density of the KT-2 beam was 99.8 percent of the control concrete. The average f'_c of cores taken from near the discharge location was approximately 6,900 psi, and the reduction in f'_c between the two sides of the 11 ft long beam was only 800 psi.

The appropriateness of two different concretes for filling large scour holes under water were investigated. Two 10 yd^3 slabs were cast in 5 ft of water with inclined tremie

pipes. The two selected concretes were highly fluid and contained two different types of AWAs (Kelco and Master Builders). Two wide-flange steel columns were installed approximately 12 ft from the discharge point. The columns were approximately 3 ft apart and had closely-spaced reinforcing bars (4 in. apart) spanning horizontally between them.

Both concretes flowed well in water and resulted in smooth and flat surfaces. The mean surface slope of either slab was 1:190. The slab thickness ranged between 14.5 and 16.5 inches. The average in-place density and f'_c values of each slab were approximately 98.7 and 94.5 percent, respectively, of control specimens. Inferior concrete was obtained from behind the discharge location because of the back flow of segregated and water diluted concrete there. Similarly, low in-place properties were measured from the area beyond the horizontal steel bars since the funnelling of the concrete past these bars caused it to severely segregate and intermix with water.

Based on the above test results, the following conclusions are presented:

A. Concretes similar to those recommended in Chapter Eight (MSFMPRO, KELCO, etc.) are suitable for casting reinforced slabs and beams or filling large and deep scour holes under water. These concretes should be modified slightly by increasing their HRWRA contents and reducing their AWA concentrations to secure self-leveling properties. Typical W/CMs can range between 0.45 and 0.48, although lower values are desired. A de-air admixture should be incorporated whenever the AWA causes air entrapment.

B. High initial flow values (28 ± 1 in.) should be secured for the concrete to flow readily and self-level. The washout mass loss of the concrete should not exceed 10 percent after three test drops in water.

C. Although the washout susceptibility of the above concretes are greater than those developed in the previous chapter, their high fluidity values should enable them to intermix in place, self-consolidate and offset some of the

damage caused by water dilution. The bottom of the placement device should be submerged beneath freshly-placed concrete, and the free-fall of the concrete in water should be avoided.

D. In mixing such concrete, the AWA should be administered last after the mixing water and HRWRA have been added to fluidize the mixture. The concrete should then be mixed for a minimum of 5 minutes. Highly fluid concretes containing AWAs should not present problems in cleaning mixers after the completion of casting.

E. The discharge of concrete should proceed without interruption in order to maintain sufficient kinetic energy to overcome the internal shear resistance of the concrete and the external friction caused by various obstacles.

F. Reinforcing bars should be well spaced (more than 12 in. is desirable, 6 in. minimum) to facilitate the movement of concrete through them and reduce any turbulence and subsequent disturbance. If closer spacing is required, bars may have to be bundled together.

G. Concrete similar to the KT-2 mixture is suitable for casting reinforced concrete slabs and beams under water. Flat and smooth surfaces (1:90) can be attained. An average in-place relative density of 99.8 percent and f'_c values of 7,000 psi can be obtained after 28 days of curing.

H. Unreinforced slabs with smooth surface and flat slopes (1:190) can be obtained by casting highly fluid concrete mixtures similar to the K-FIELD and MB-FIELD concretes. Average in-place density and f'_c values can be as high as 99 and 95 percent, respectively, of control concrete values.

I. As concluded in Chapter Eight, the bottom of the inclined pipe should be positioned at the edge of the casting area to minimize the back flow of concrete. In casting large areas under water, concrete can be expected to flow at least 10 to 12 ft without exhibiting much reduction in quality.

CHAPTER TEN

REPAIRING THIN SCOUR HOLES WITH STIFF CONCRETE

10.0 Scope of Experimental Work

In repairing thin scour holes (less than one foot deep) under water, concrete may have to be dropped freely in water because of the limited depth of the repair area. Furthermore, such concrete may also be subjected to moving water and surf. Fluid concretes developed in the last three chapters are not suitable for these applications since they were proportioned for high mobility and self-compaction with only moderate resistance to water erosion.

Thin scour holes may be repaired using highly washout-resistant and stiff concrete that can be cast under water then spread and compacted in place. Concrete suitable for such applications should possess the following properties:

A. Superior cohesiveness and resistance to water erosion.

B. Sufficient plasticity to minimize the underwater compaction effort.

C. High strength and wear resistance.

D. Controlled delay in setting time until completion of underwater operations.

This chapter is devoted to developing such sticky concrete mixtures and evaluating the feasibility of spreading and compacting them in water. The suitability of repairing shallow scour holes under water using these concretes is established. Preliminary guidelines for casting and processing highly washout-resistant concrete under water are offered in Chapter Eleven, however, further work is needed in this area.

The experimental work was divided into three parts. The first dealt with the development of stiff concretes where eight trial mixtures were prepared and four promising

concretes were selected and fully evaluated. The concretes incorporated two kinds of AWAs and two types of fibers. The feasibility of dropping these concretes in water and compacting them into place was addressed in the second phase of this study. A steel fibrous concrete and a plain concrete were dropped in 12 in. of water. The concrete was then compacted using a small concrete roller that was dragged back and forth gently over the concrete. The final slab thickness and in-place concrete density were measured for slabs subjected to 4, 8 and 16 passes. These values were compared to similar results obtained from slabs compacted above water using the same concrete roller and an equal number of passes.

The third phase of this study dealt with optimizing lift thicknesses and determining proper compaction efforts needed to secure flat and sound repair surfaces. A promising plain concrete was cast in a large placement box filled with 2 ft of water using a bottom-dumping skip. The original slab thickness, the size and weight of the roller and the number of passes were varied. The in-place density, f'_c and bond strength to underlying concrete of three slabs were evaluated. Preliminary recommendations regarding mix proportionings, workable lift thicknesses and compaction efforts were established.

10.1 Materials and Test Methods

Hard pea gravel of 3/8 in. nominal size was used to improve the wear resistance of the concrete and enable the casting of thin overlays. Sikament 86 HRWRA was used to decrease the W/CM. Master Builders and Protex AWAs were employed to enhance the cohesiveness and washout resistance of the concrete.

The influence of special fibers on the abrasion resistance of stiff concrete was investigated. Twisted steel fibers measuring one inch in length were used. These fibers were employed because of their partially rough interior surface which can enhance bonding to cement paste, and their smooth exterior surface which can reduce balling. Polyethylene

fibers 0.5 in. in length and 0.038 mm in diameter were also used. The yield strength and modulus of elasticity of the polyethylene fibers were 375 and 1,700 ksi, respectively.

The charging sequence of concrete-making materials were identical to those described in section 7.2. The AWA was blended with the cementitious materials as a dry powder. The fibers were the final ingredient which was added to the fresh concrete. Temperature and relative humidity conditions during batching and curing were identical to those presented in section 7.2. Tests similar to those described in Chapter Five were adopted to investigate several important physical and mechanical properties.

10.2 Phase I - Concrete Development and Evaluation

10.2.1 Trial Mixtures A total of eight trial mixtures were prepared in 0.5 ft^3 batches. Their mix proportions along with the evaluated slump and flow values, unit weights, air contents, washout weight losses and final setting times are presented in Table 47 (Appendix F). The average cement content of the stiff concrete was 750 lb/yd^3. Approximately 115 lb/yd^3 of silica fume was incorporated to improve the wear resistance and bond development of the hardened concrete. The sand content was fixed to 46 percent of the total aggregate volume to improve the plasticity of the fresh concrete. The W/CMs of trial mixtures ranged between 0.30 and 0.35. Enough AWA was administered to limit the washout weight loss to one percent after 10 test drops in water. A de-air admixture was incorporated to de-foam any entrapped air caused by the AWA.

Repair concretes should maintain their plasticity for a few hours until they are cast, spread and compacted in place. They should set soon thereafter to minimize water erosion. Stiff concretes incorporating high doses of HRWRAs and AWAs exhibited final setting times of 48 hrs. (Mixes 23 and 24). However, the addition of $CaCl_2$ as 2 and 1.5 percent of the weight of cementitious materials helped reduce the final setting time to 8.5 and 11 hrs., respectively (Mixes 23A and 24A).

The addition of small volumes of fibers did not significantly impair the workability of the concrete. For example, the initial flow value was reduced from 13.5 to 12 in. when the polyethylene fiber was incorporated as 0.5 percent of the concrete volume (Mix 25A). Similarly, the flow value decreased from 13.2 to 10.5 in. when the steel fibers were added as 0.75 percent of concrete volume (Mix 26A).

10.2.2 Final Mixtures The mix proportions of four optimized concretes are summarized in Table 13. The STIFF-PRO and STIFF-M.B. concretes had similar mix designs, except for using the Protex and Master Builders AWAs, respectively. The fibrous concretes (STIFF-STEEL and STIFF-POLY) had slightly higher W/CMs than the plain concretes. Concretes were prepared in 1.8 ft^3 batches and had low air volumes (1 to 1.5 percent).

Table 13. Concrete Mix Proportions

DESIGNATION	CEMENT	MINERAL ADDITIVES			TOTAL CM	W/CM	AGGREGATE	
		SF	FA	SLAG			SAND	P. G.
	PCY	% OF CEMENT WT.			PCY		PCY	
STIFF-PRO	744	15	0	0	856	0.32	1304	1550
STIFF-M.B.	749	15	0	0	862	0.32	1296	1541
STIFF-STEEL	752	15	0	0	865	0.33	1274	1515
STIFF-POLY	740	15	0	0	851	0.34	1249	1485

DESIGNATION	ADMIXTURES FL OZ/ 100# CM				AWA		CACL2	UNIT WT.	AIR VOL
	HRWRA	WRA	AEA	DE-AIR	% CM	TYPE	% CM	PCF	%
STIFF-PRO	37	0	0	0.2	0.75	PROTEX	2	148.6	1 - 1.5
STIFF-M.B.	34	0	0	0.2	1.7	M. BUILD.	1.5	148.5	1 - 1.5
STIFF-STEEL	38	0	0	0.2	1.5	M. BUILD.	1	150.8	1 - 1.5
STIFF-POLY	38	0	0	0.2	1.5	M. BUILD.	1	147	1 - 1.5

The concrete mixtures had low consistency levels but not "zero-slump" values as in conventional roller-compacted concrete. Figures 63 and 64 show the slump and flow values, respectively, over 90 minutes. The initial flow values of four concretes were 11 $\pm$ 1 inches. All concretes had similar rates of fluidity losses, with the STIFF-M.B. mixture

showing slightly favorable results. The flow values reflected less reduction in consistency than observed with the slump test because of the dynamic nature of the flow test. All mixtures maintained positive slump values after 90 min., suggesting that the concrete remained plastic and workable for at least 90 min. after mixing.

None of the stiff concretes suffered any bleeding. The washout weight losses are plotted in Figure 65. All concretes had similar weight reductions which ranged from 0.75 to 1 percent after 10 test drops in water. The STIFF-M.B. mixture exhibited slightly better resistance to water dilution than the other concretes. Table 14 lists the setting times of the concretes at approximately 67^0 F. The initial setting time ranged from 6 to 11 hours. The spread between the initial and final setting times was approximately 1.5 hours. Fibrous concretes exhibited slightly faster stiffening rates than the other mixtures.

Table 15 summarizes the average strength results of standard specimens cast and consolidated on land. All concretes exhibited high early strengths. The average 7 day f'_c was approximately 77 percent of the strength after 56 days. It is interesting to note that the strength values of the stiff concretes are slightly lower than those expected for concretes containing such relatively high cement and silica fume contents and low W/CMs. However, as indicated in section 7.5, the incorporation of high amounts of AWAs in concrete containing low W/CMs could result in some strength reduction. Higher strength values might be achieved if the AWA is added pre-hydrated with water and added in a slurry form at lower concentrations.

Fiber-reinforced concretes had higher splitting tensile strengths than non-fibrous concretes, however, their flexural strengths were lower than the plain concretes. The reduced flexural strength of the STIFF-POLY concrete is believed to be caused by the weak bonding and short anchorage between the polyethylene fibers and the cement paste. Similarly, the partially smooth surface of the steel fibers is believed to prevent the development of continuous bonding between the steel fibers and the cement paste. Hence, the presence of initial discontinuity there can reduce the flexural strength.

The benefit of using fibrous concrete to cast a wearing surface over the base slab of hydraulic structures can be appreciated by assessing not only the flexural strength, but also the toughness and wear resistance of the concrete. Figure 66 plots the load versus mid-span deflection of concrete beams loaded at third-point locations. Unlike plain concrete beams which cracked and failed at peak flexural stresses, concrete containing a low fiber content exhibited good post-cracking behavior which reflects high ductility and toughness values. Steel fiber-reinforced concrete with partially bonded fibers exhibited high ductility and ultimate strain values which were approximately 10 times greater than those of plain concrete. The STIFF-POLY concrete had high strain capacity values, as well as lower ductility than the STIFF-STEEL because of its lower modulus of elasticity.

The results of the underwater abrasion tests for concrete cast above and under water are summarized in Table 16. In general, the 72 hr. abrasion weight loss of concretes cast in air were 2.1 $\pm$ 0.2 percent. The STIFF-STEEL and STIFF-POLY mixtures had 72 hr. weight loss values 0.2 percent higher and 0.2 percent lower than their corresponding plain concrete (STIFF-M.B.), respectively. The additional wear damage due to casting and compacting concrete under water ranged between 24 and 67 percent after 72 hrs. of testing. All concretes, except the STIFF-PRO, had approximately 3 percent cumulative weight losses after 72 hrs. of testing. The STIFF-PRO mixture suffered a 4 percent cumulative weight loss. The comparison of the abrasion weight losses of stiff concretes to those of fluid mixtures (Chapter Seven, Table 9) indicate that the former set exhibited at least 25 percent greater abrasion-erosion resistance than the best performing fluid concrete.

The temperature developments of two plain concretes were monitored for 6 days (section 7.6.9). These temperatures are plotted in Figure 67 along with that of the CONTROL fluid concrete from Chapter Seven. Stiff concretes incorporated high contents of $CaCl_2$ and exhibited early rises in temperature. However, they did not develop excessive heat generation and attained maximum temperatures slightly higher than 110^0 F. The peak temperatures were reached approximately 5 to 10 hrs. after the final setting.

Table 14. Summary of Setting Times

	SETTING TIME, HOURS	
CONCRETE TEMP. (F)	65 - 70	
MIX -- CACL2 (% CM)	INITIAL	FINAL
STIFF-PRO -- 2	9	10.5
STIFF-M.B. -- 1.5	11	12.5
STIFF-STEEL -- 1	7.5	8.45
STIFF-POLY -- 1	6	7.25

Table 15. Strength Results

		STRENGTH, PSI						
		COMPRESSIVE			SPLIT. TENSILE			M. R.
FINAL MIXTURE	W/CM	7 D.	28 D.	56 D.	7 D.	28 D.	56 D.	56 D.
STIFF-PRO	0.32	7010	9195	10480	720	945	960	1040
STIFF-M.B.	0.32	7905	9610	10270	740	880	980	1175
STIFF-STEEL	0.33	8305	9615	9955	1040	1185	1155	950
STIFF-POLY	0.34	7120	9285	8875	895	1085	1080	995

Table 16. Summary of Abrasion-erosion Results

	% CUMULATIVE ABRASION WT. LOSS					
	CAST ON LAND					
HOURS OF TESTING	12	24	36	48	60	72
STIFF-PRO	0.3	0.7	0.9	1.5	2	2.4
STIFF-M.B.	0.2	0.6	1	1.4	1.8	2.3
STIFF-STEEL	0.6	0.9	1.3	1.8	2.1	2.5
STIFF-POLY	0.2	0.4	0.8	1.3	1.7	2.1

	CAST UNDER WATER						% SPREAD
HOURS OF TESTING	12	24	36	48	60	72	@ 72
STIFF-PRO	0.9	1.9	2.6	3.2	3.6	4	67
STIFF-M.B.	0.1	0.1	0.6	1.4	2.4	3	30
STIFF-STEEL	0.6	0.8	1.3	2	2.5	3.1	24
STIFF-POLY	0.3	0.6	1.1	1.6	2.3	2.9	38

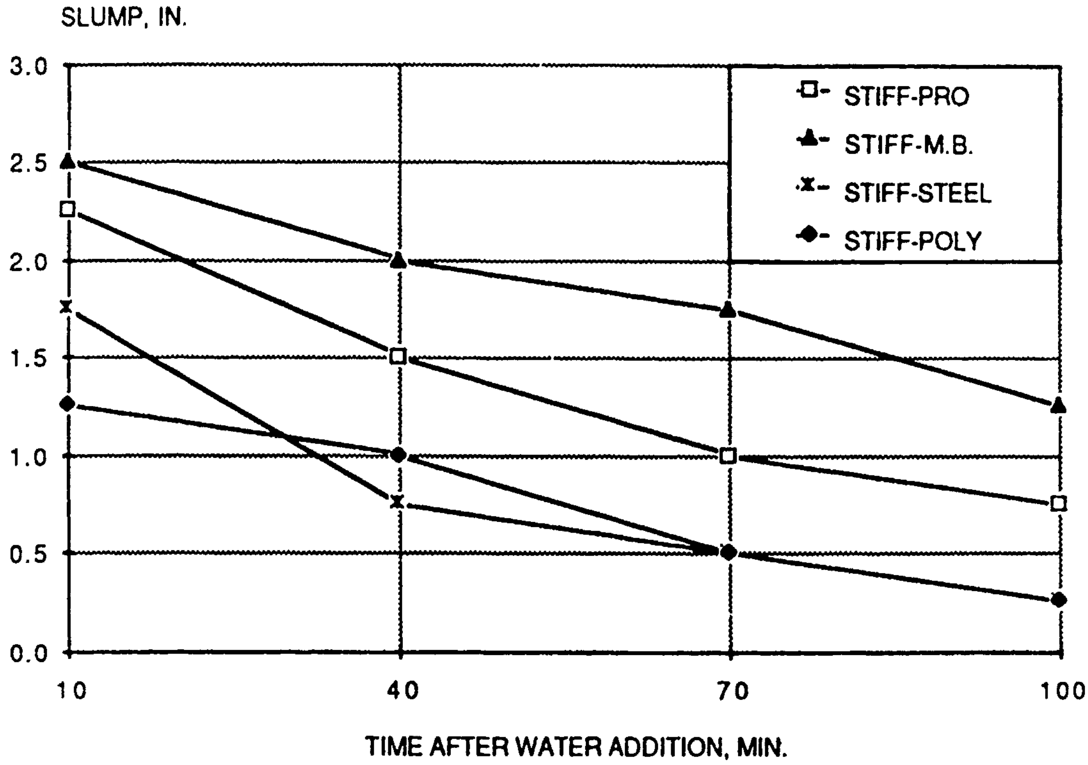


Fig. 63--Slump Retention of Stiff Concretes

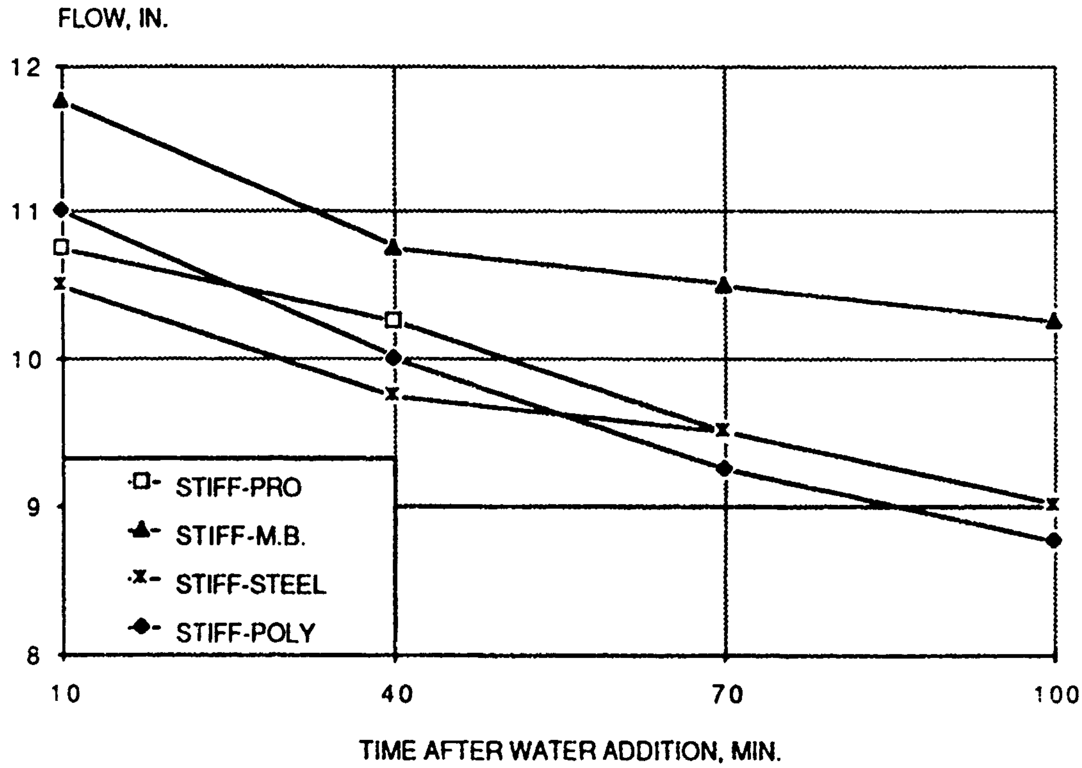


Fig. 64--Flow Retention of Stiff Concretes

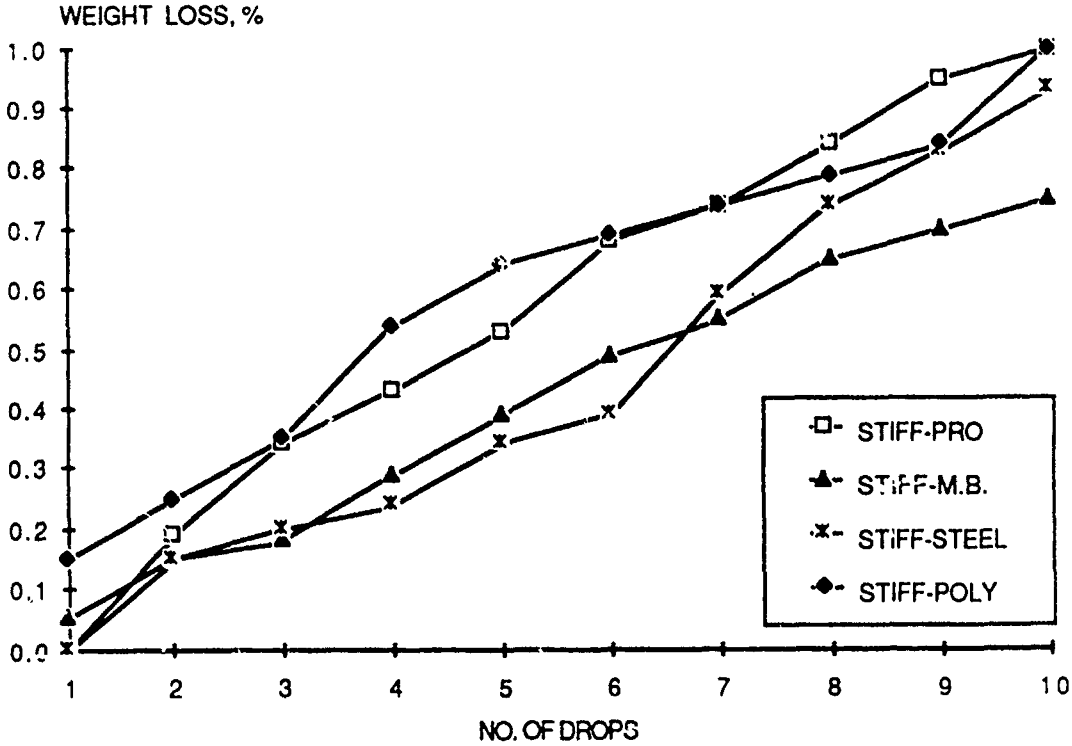


Fig. 65--Water Erosion Results

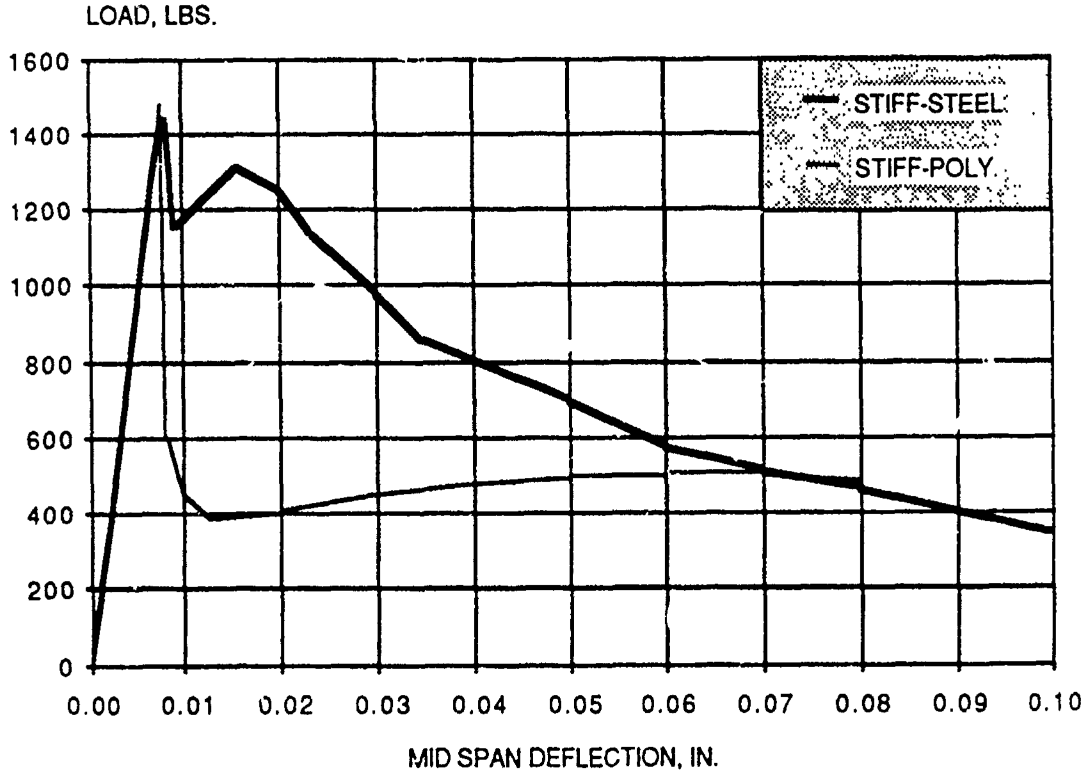


Fig. 66--Load - Deflection of Fibrous Beams

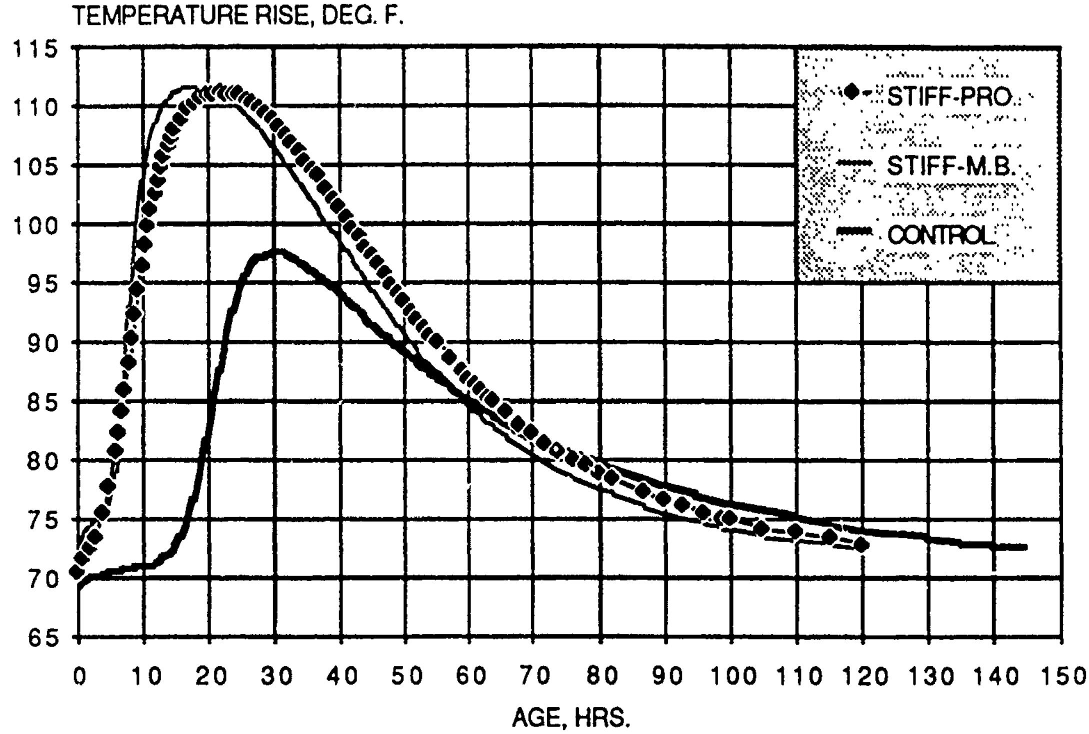


Fig. 67--Temperature Developments

10.3 Phase II - Underwater Versus Above water Compaction

10.3.1 Objective Among the important factors affecting the final quality of underwater compacted concrete are the plasticity and compatibility of the mix, its resistance to water erosion, degree of consolidation and abrasion resistance. This section attempts to establish the benefit of consolidating stiff concrete under water by comparing the relative in-place density and thickness values of concrete slabs cast and processed in water to those cast and compacted on land.

10.3.2 Test Procedures The STIFF-M.B. and STIFF-STEEL concretes were selected for this study. A bottomless box measuring 12 x 12 x 3.5 in. was utilized. The bottom of the box was covered with plastic to retain the fresh concrete which was placed there loosely. The upper surface of the concrete was struck flat with the top of the box. The

skip was then positioned over a 48 x 42 in. placement box filled with 12 in. of water. The plastic at the bottom of the casting box was quickly removed, thus allowing the sticky concrete to fall through the water in one continuous mass.

A small concrete roller measuring 9.5 in. in diameter and 14 in. in length was used to consolidate the concrete. The metal-lined roller provided an approximate net pressure of 3.5 lb/in. when submerged in water. The roller was positioned at one end of the basin and was pushed gently by hand over the concrete to spread and consolidate it (Figures 100 and 101, Appendix F).

Three slabs were prepared for each of the plain and fibrous concretes by consolidating the cast concrete 4, 8 and 16 times. The concrete was kept submerged for one day before removing it from water and storing it in a lime-saturated bath for 6 days. The average thickness and density of each slab were then determined. The density results were compared to those of 3 x 6 in. control cylinders that were cast and vibrated on land and received the same curing as their corresponding slabs.

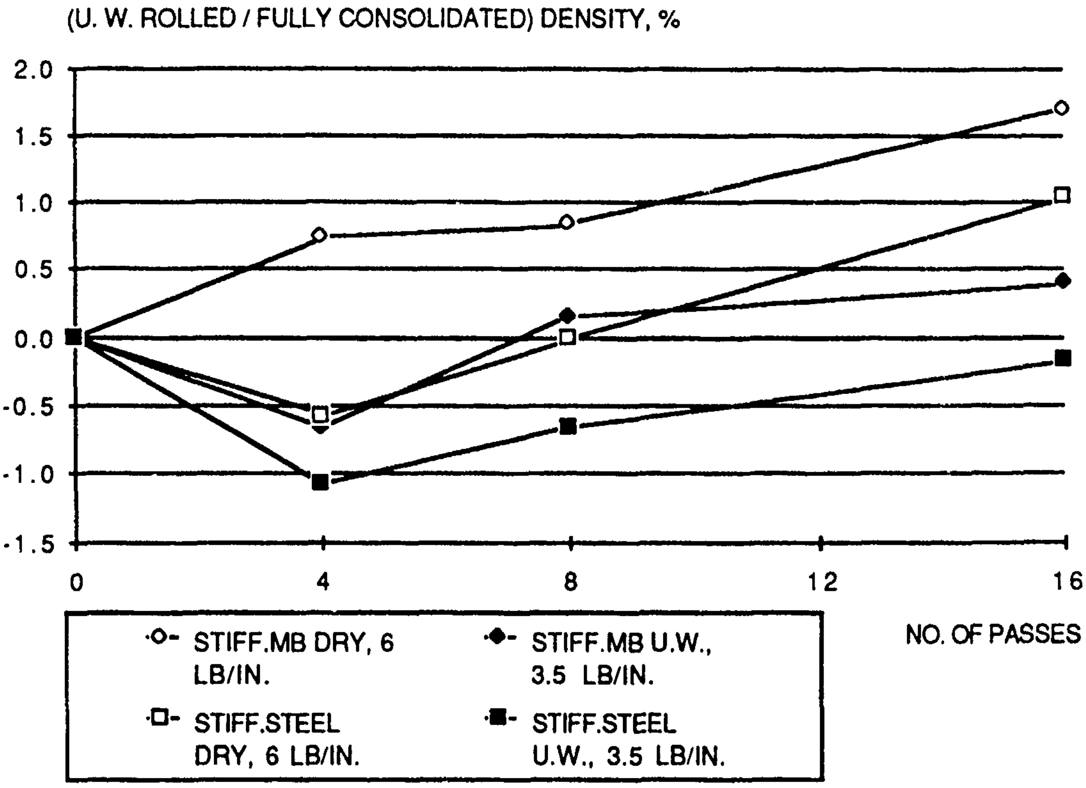
The same set of experiments was repeated for concrete cast and consolidated above water. Again, eight slabs were formed by spreading and consolidating a 12 x 12 x 3.5 in. layer of fresh concrete 4, 8 and 16 times using the same roller that was employed for underwater compaction. The roller provided a 6 lb/in. net pressure. The average thickness and density of the slabs were determined. Again, the slabs were covered with wet burlap and plastic sheets for one day, then stored in lime-saturated water for 6 days.

Unlike conventional roller-compacted concrete, the underwater-processed concrete was spread and consolidated at the same time. Therefore, the exerted passive pressure is believed to result in shear failure planes within the fresh concrete which enable it to spread, intermix and consolidate.

10.3.3 Test Results Underwater-consolidated slabs had smoother surface textures than those compacted above water. Similarly, plain concrete slabs had smoother surfaces than fiber-reinforced ones. The surface texture appeared to improve with the number of passes.

Figure 68 shows the changes in average densities of all 12 tested slabs from the density values of control specimens that were cast in 3 x 6 in. molds above water. The density of dry-consolidated plain concrete improved with the number of compaction passes. However, the density of the fibrous concrete compacted above water increased linearly between 4 and 16 passes, after exhibiting approximately 0.5 percent density reduction after four passes. The relative densities of underwater-cast plain and fibrous concretes also suffered slight losses ranging between 1 and 0.5 percent, respectively, after four passes. However, the density values of these two concretes increased linearly after 8 and 16 passes. At the completion of 16 passes, the relative density of underwater-processed plain concrete was 0.4 percent higher than that of control concrete. Similarly, the relative density of underwater-processed fibrous concrete was only 0.1 percent lower than control concrete at the completion of 16 passes.

Figure 69 illustrates the average thickness of each slab after 4, 8 and 16 passes. In general, the thickness of plain concrete decreased more rapidly with the number of compaction passes than that of fibrous concrete indicating that plain concrete is easier to consolidate. For example, the thicknesses of dry-cast and underwater-cast STIFF-M.B. concrete slabs were 1.4 in. after four passes. On the other hand, these values were 2.4 and 1.9 in., respectively, for the STIFF-STEEL concrete. The depth of underwater-processed concrete was approximately 0.25 in. thinner than that of concrete processed in air after 8 and 16 passes, despite the fact that the underwater compaction pressure was less than the compaction pressure above water. The same phenomenon was observed with the fibrous concrete at the completion of 16 passes.



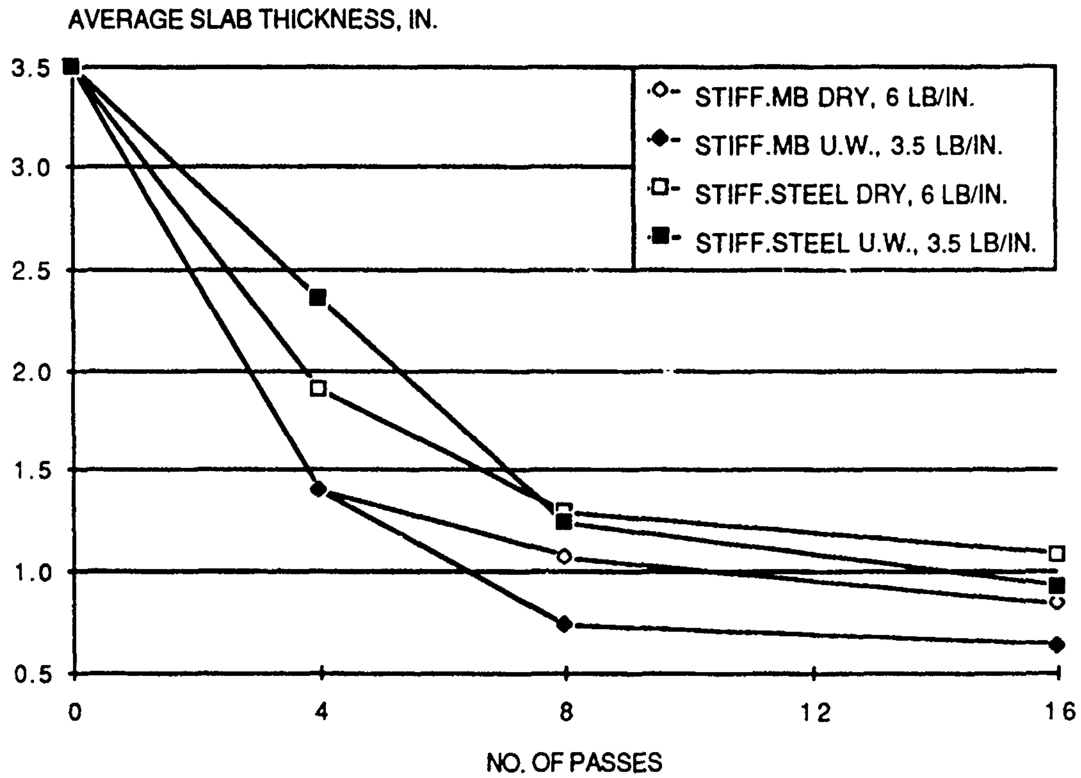


Fig. 68 and 69--Relative Density and Thickness of Compacted Slabs

10.4 Phase III - Underwater Compaction - Laboratory Trials

The work described in this section was undertaken to determine suitable lift thicknesses and proper compaction efforts necessary to secure smooth and sound repair surfaces. A total of six underwater placements were carried out in the laboratory. The first three were trial placements and were used to establish manageable lift depths and select proper compaction rollers. The other three trial placements were successful, and their results are presented below.

The STIFF-M.B. concrete was selected for this investigation. It was cast under water using a bottom-dumping skip and then compacted into place with concrete rollers. The initial thickness of the cast concrete, number and arrangement of lifts, compaction pressure and number of passes were varied. Two concrete drums were fabricated for spreading and consolidating the concrete. The characteristics of these rollers are listed in Table 17. A steel rod was provided along the axis of each drum where a steel cable was attached to pick up and maneuver the heavy roller (Figure 102, Appendix F).

Table 17. Description of Concrete Rollers

ROLLER DESIGNATION	DIAMETER IN.	LENGTH IN.	WEIGHT LB.	STATIC PRESSURE, LB/IN.	
				ON LAND	UNDER WATER
MEDIUM	14	22	310	14	8.5
LARGE	17	23	480	21	12.5

The placement box measured 6 x 3 feet. Its bottom was lined with a concrete base slab ("old" concrete) measuring 3 in. in depth which was cast above water. The "old" concrete contained approximately 660 lb/yd^3 of cement, 50 lb/yd^3 of silica fume and had a W/CM of 0.36. The surface of the base slab was roughened with a steel wire brush to expose coarse aggregate and enhance the bonding to underwater-cast ("new") concrete, as

described in section 8.1.1. After cleaning the "old" concrete surface, the basin was sealed and filled with 2 ft of water. The selected roller was then lowered at one end of the box.

Freshly-mixed concrete was loosely placed above water in a bottom-dumping skip measuring 18 x 18 x 6.5 in. (Figure 103, Appendix F). The top of the fresh concrete was struck flat, then the skip was covered with a plate to minimize disturbance to the concrete when lowered in water. The skip was gently lowered into water until its bottom was approximately 12 in. above the base slab (Figure 104, Appendix F). A quick-release bottom gate was then opened allowing the sticky concrete to drop through water. A water hose was installed at the bottom of the basin to circulate water in the placement box during under water operations.

The concrete was spread and compacted by gently pulling the roller back and forth over it. Sounding data was collected prior to underwater processing and after a predetermined numbers of passes to monitor the changes in slab thicknesses. The concrete was kept submerged for a few days before dewatering the basin. Cores were taken from the underwater-cast and base slabs in areas where the thickness of the "new" concrete exceeded 3 inches. Cores were kept in lime-saturated water at 73 ± 3^0 F until they were tested after 104 to 110 days of curing. Conventional 3 x 6 in. control cylinders were prepared above water and received similar curing as their corresponding slabs.

The density values of the cores were measured prior to and after cutting the core ends to remove loose materials. The unit weight and f'_c values were tested and compared to those of control specimens. The bond strength between "new" and "old" concretes was also determined using the point-load tensile test (section 5.2.3). The measured in-place properties are plotted along the slab with the origin considered to be the left-front corner of the placement box. The legends of the plotted data points are the same as those described in section 8.2.3.

10.5 SLAB NO. 1

10.5.1 Casting Sequence and Slab Appearance Shallow and small pockets were formed in the base slab by removing some of the freshly-cast "old" concrete. Two 6.5 in. concrete lifts were placed in water near one another along the basin, resulting in a total unconsolidated slab measuring 36 x 18 x 6.5 inches. The concrete was first compacted twice with the medium roller, since it was determined during the trial placements that the medium roller was initially needed to flatten the 6.5 in. vertical edge of the slab and form a ramp before employing the large roller. The concrete was then compacted 24 times with the large roller. The resulting length and width of the consolidated slab were approximately 4 x 2 ft, and its average thickness at the center was approximately 4.5 in., and the depths at both ends were 2.5 and 1.4 inches. The surface texture of the concrete was very smooth (Figure 70), however, there was a mound at the center of the slab.

10.5.2 Unit Weight (Figure 71; Table 48 of Appendix F) The relative densities of cut cores were 100 $\pm$ 0.5 percent of the control density, and the average relative density was 99.8 percent. The increase in concrete density due to the removal of core ends was limited to 0.5 percent. These results indicate that the underwater compaction improved the in-place quality of the concrete and overcame water disturbance caused by underwater handling and compaction.

10.5.3 Compressive Strength (Figure 72; Table 49 of Appendix F) The f'_c of six cores ranged between 81 and 86 percent of the control strength. The average f'_c was 85.1 percent, or 9,405 psi.

10.5.4 Bond Strength (Figure 73; Table 50 of Appendix F) Concrete cast in water developed adequate bonds with the base slab. The average bond strength between the "new" and "old" concretes was 285 psi. This was approximately 65 and 53 percent of the point-load tensile strengths of the "old" and "new" concretes, respectively.

Fig. 70--Picture of SLAB NO. 1

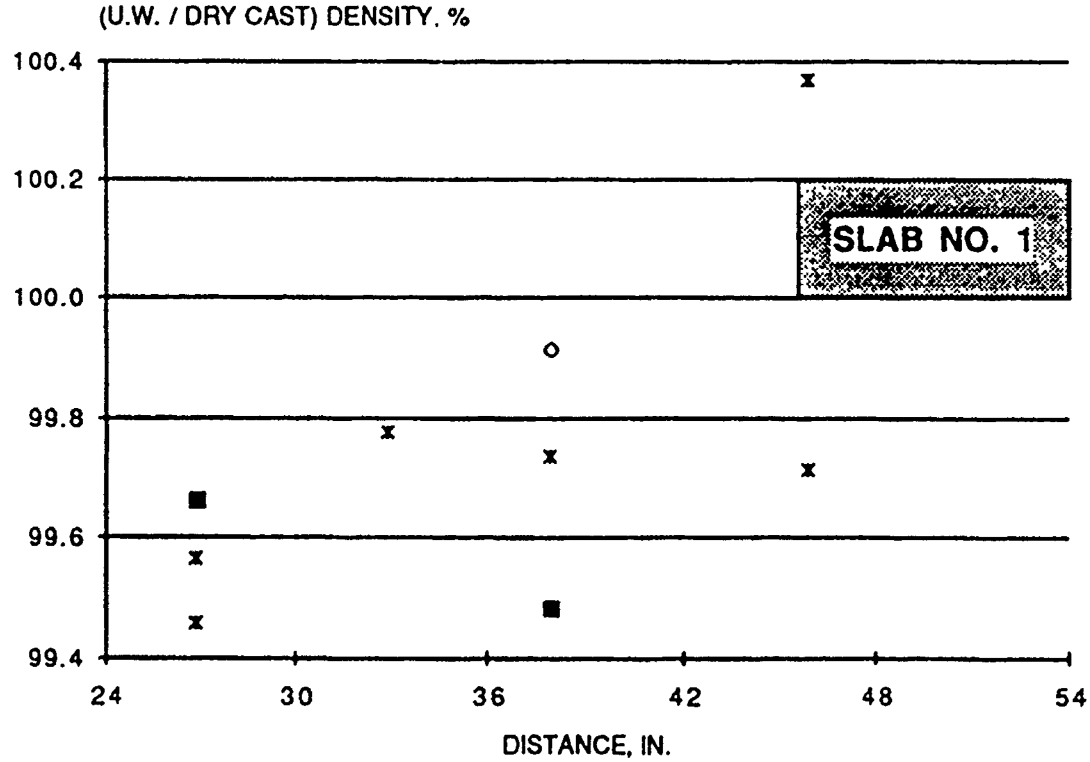


Fig. 71--Unit Weight along SLAB NO. 1

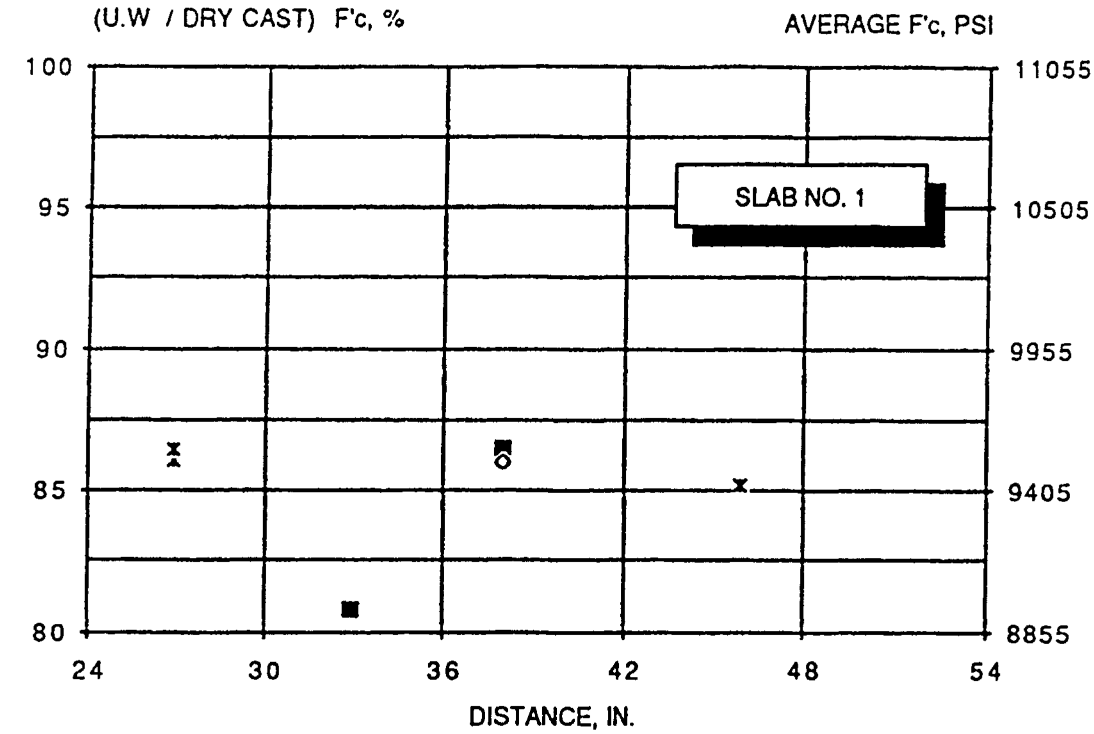


Fig. 72--Compressive Strength Values along SLAB NO. 1

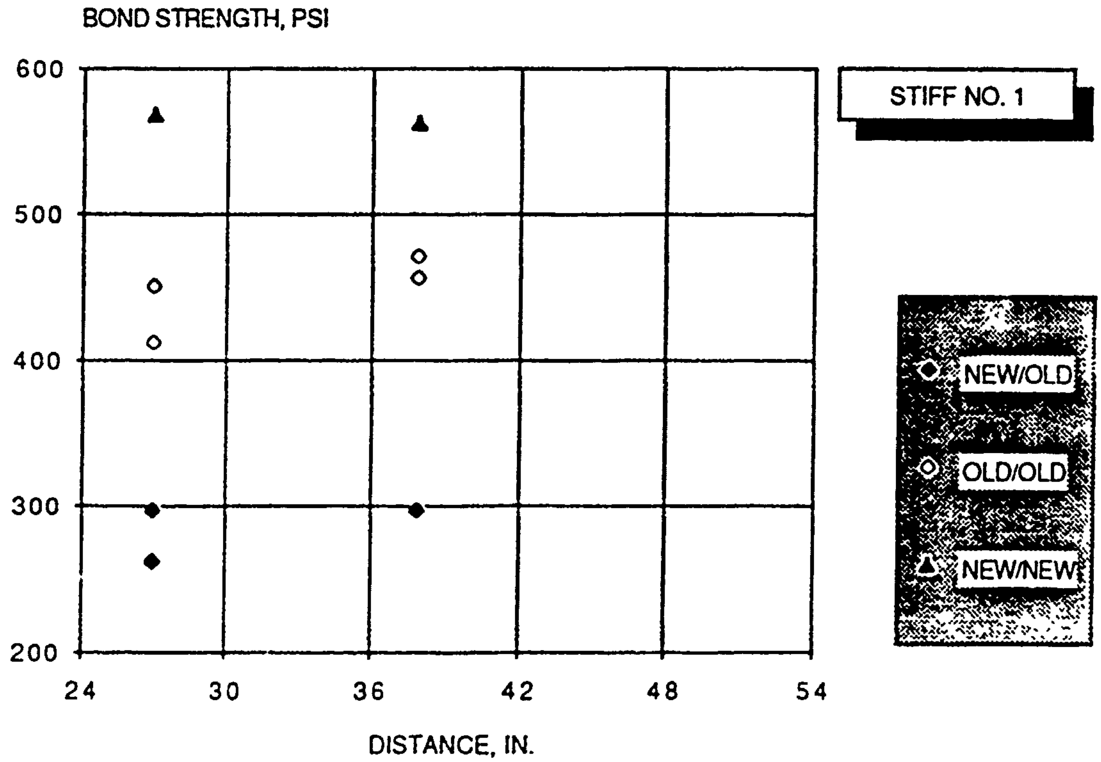


Fig. 73--Bond Strength Values along SLAB NO. 1

10.6 SLAB NO. 2

10.6.1 Casting Sequence and Slab Appearance Two 5 in. thick concrete lifts were cast on top of one another. The first lift (Lift A) measured 18 x 18 x 5 in. and was compacted twice with the medium roller and then four times with the large roller. At the completion of these six passes, Lift A measured approximately 4 x 1.75 ft and was 2 in. thick at the center and one inch thick at either end.

The second lift (Lift B) was cast over the center of the first compacted lift. Lift B had the same initial dimensions as Lift A and was also consolidated twice with the medium roller and four times with the large one. The processed second lift measured 2.5 x 2 feet. The final average depth of both lifts was approximately 4.5 in. at the center. This thickness decreased gradually to approximately 3.5 in. at quarter points and 0.75 in. at the ends. In both lifts, the maximum reduction in thickness occurred after two passes with the large roller. The surface of the concrete was smooth, as shown in Figure 74.

10.6.2 Unit Weight (Figure 75; Table 51 of Appendix F) The average relative density of seven cores was 99 percent of the control density with the majority of the tested values being within 0.1 percent of this average. The increase in density due to the removal of the core ends was limited to 0.25 percent.

10.6.3 Compressive Strength (Figure 76; Table 52 of Appendix F) In-place f'_c values varied from approximately 85 to 94 percent of control strength. The average in-place f'_c of five cores tested 88.3 percent of control strength, or 10,170 psi.

10.6.4 Bond Strength (Figure 77; Table 53 of Appendix F) The bond strength between "new" and "old" concretes ranged from 235 to 345 psi. The average bond strength of seven tested cores was 280 psi, which was approximately 56 and 52 percent of the point-load tensile strengths of the "old" and "new" concretes, respectively.

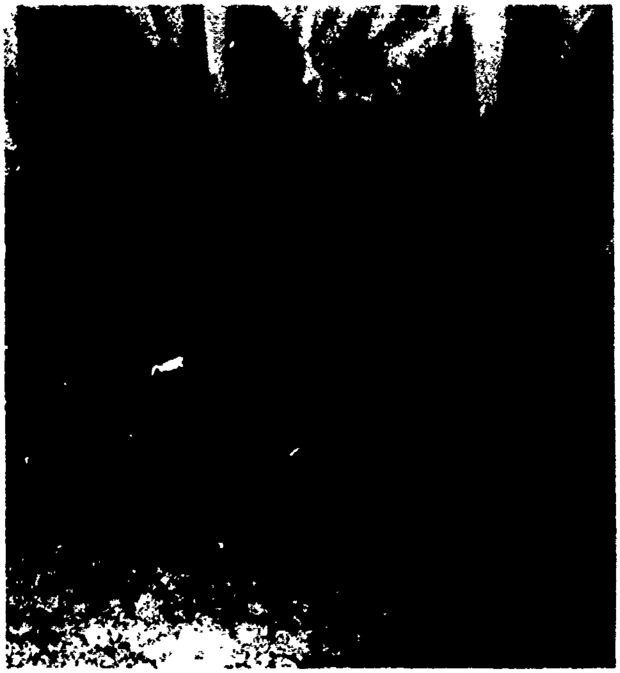


Fig. 74--Picture of SLAB NO. 2

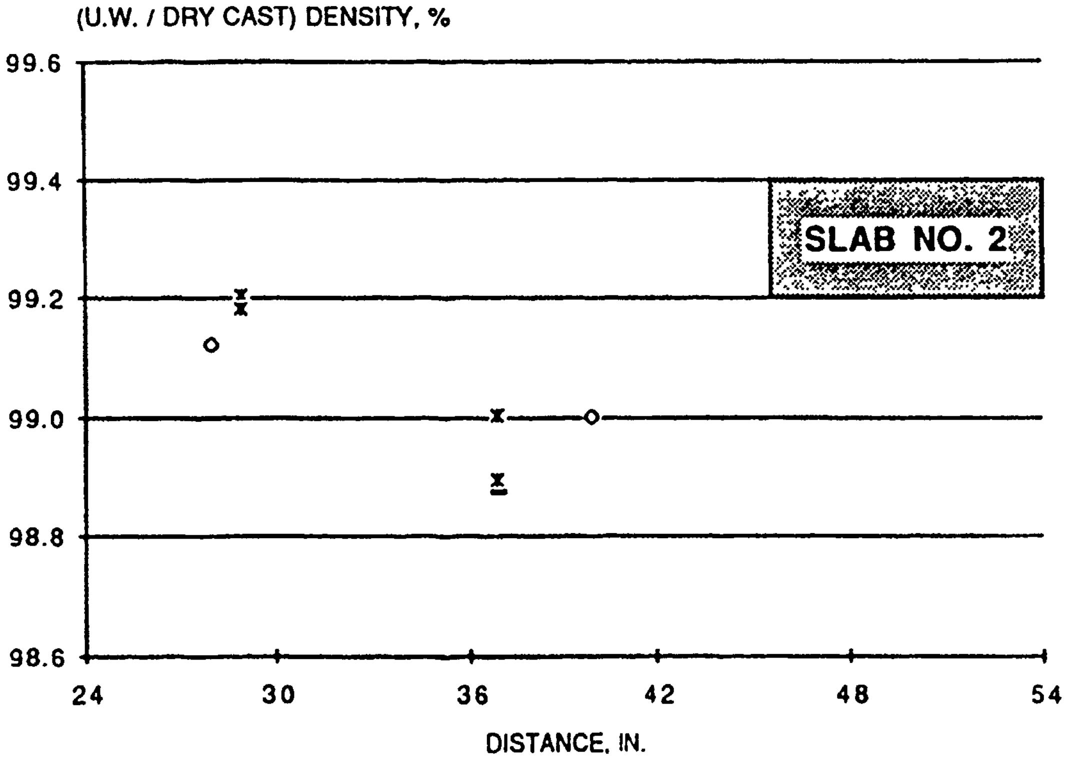


Fig. 75--Unit Weight along SLAB NO. 2

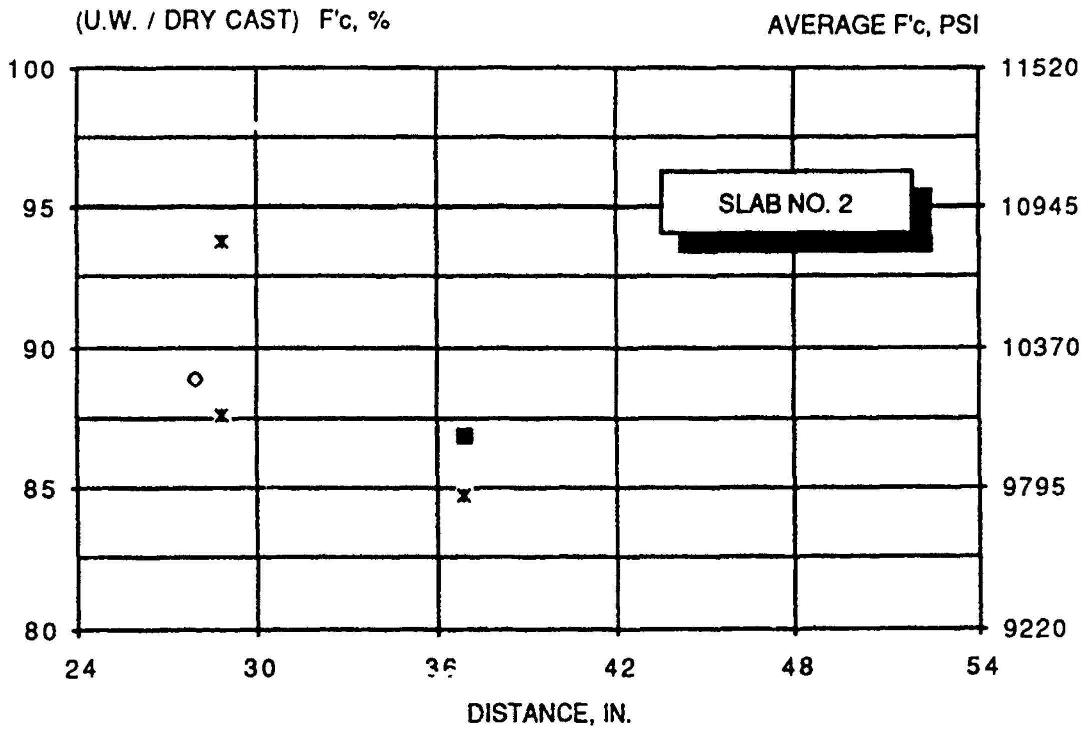


Fig. 76--Compressive Strength Values along SLAB NO. 2

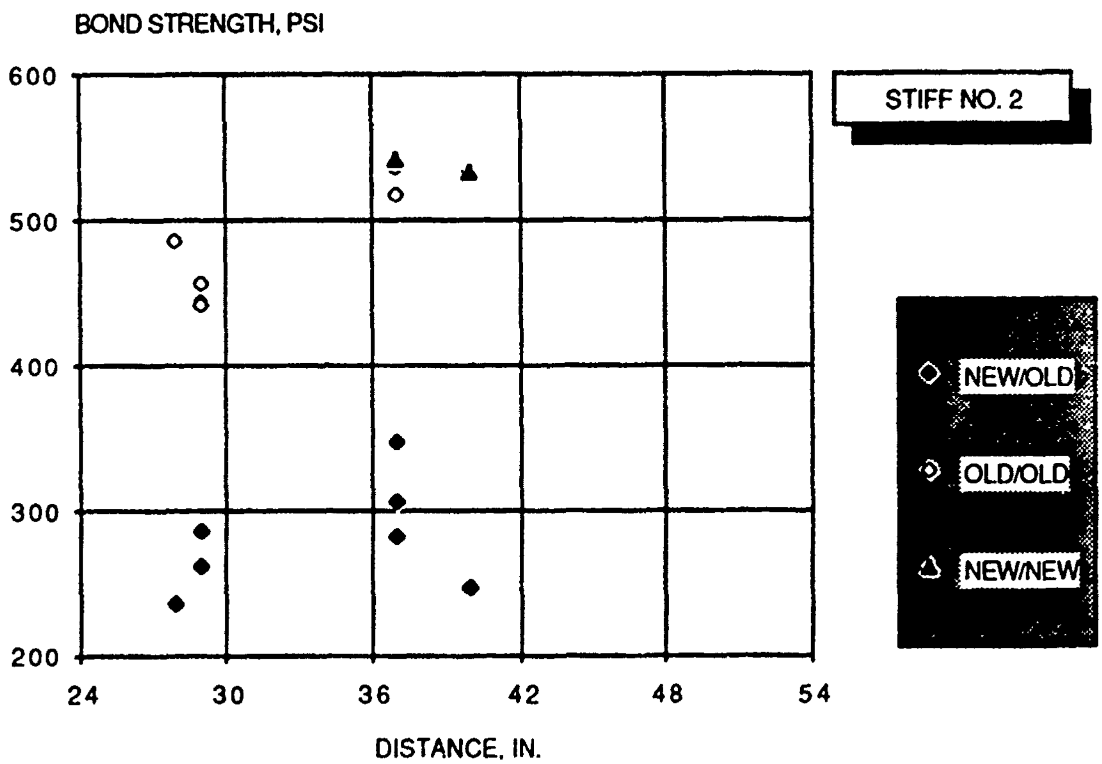


Fig. 77--Bond Strength Values along SLAB NO. 2

10.7 SLAB NO. 3

10.7.1 Casting Sequence and Slab Appearance As in SLAB NO. 2, two lifts were cast over one another. However, the initial slab thickness was reduced to 4 in. in order to reduce the required compaction effort. Lift A was cast at the center of the placement box and measured 18 x 18 x 3.75 inches. Since the lift thickness was reduced, the medium roller was not employed for flattening the vertical ends of the initial slab. Instead, the concrete was consolidated three times with the large roller. At the completion of the third pass, Lift A measured 2.5 x 1.75 ft and had average depths of 1.5 and 1.25 in. at its center and two ends, respectively.

Lift B was cast over the first one and was also consolidated three times with the large roller. In processing Lift B, the roller did not cover the entire width of the slab. Therefore, one third of Lift B was not properly consolidated, and no cores were obtained from that part. Lift B spread over Lift A and resulted in a 2.5 x 1.75 ft slab on top of the first one. Figure 78 shows the smooth surface of the compacted slab, as well as the unconsolidated side. The average combined thickness of both lifts at the center was approximately 3.75 in., which was the same as that at quarter points. For both lifts, the maximum reduction in thickness took place after two passes.

10.7.2 Unit Weight (Figure 79; Table 54 of Appendix F) The in-place relative density of six cores were 99.1 $\pm$ 0.3 percent of the control value. The increase in density due to the removal of core ends varied from 0.10 to 0.36 percent.

10.7.3 Compressive Strength (Figure 80; Table 55 of Appendix F) The f'_c of five cores ranged from 81 to 92 percent of control f'_c. The average f'_c was 86 percent, or 9,805 psi.

10.7.4 Bond Strength (Figure 81; Table 56 of Appendix F) The bond strength between "new" and "old" concretes varied between 250 and 295 psi. The average bond strength tested 275 psi. or 50 percent of the point-load tensile strength of the "old" concrete.

Fig. 78--Picture of SLAB NO. 3

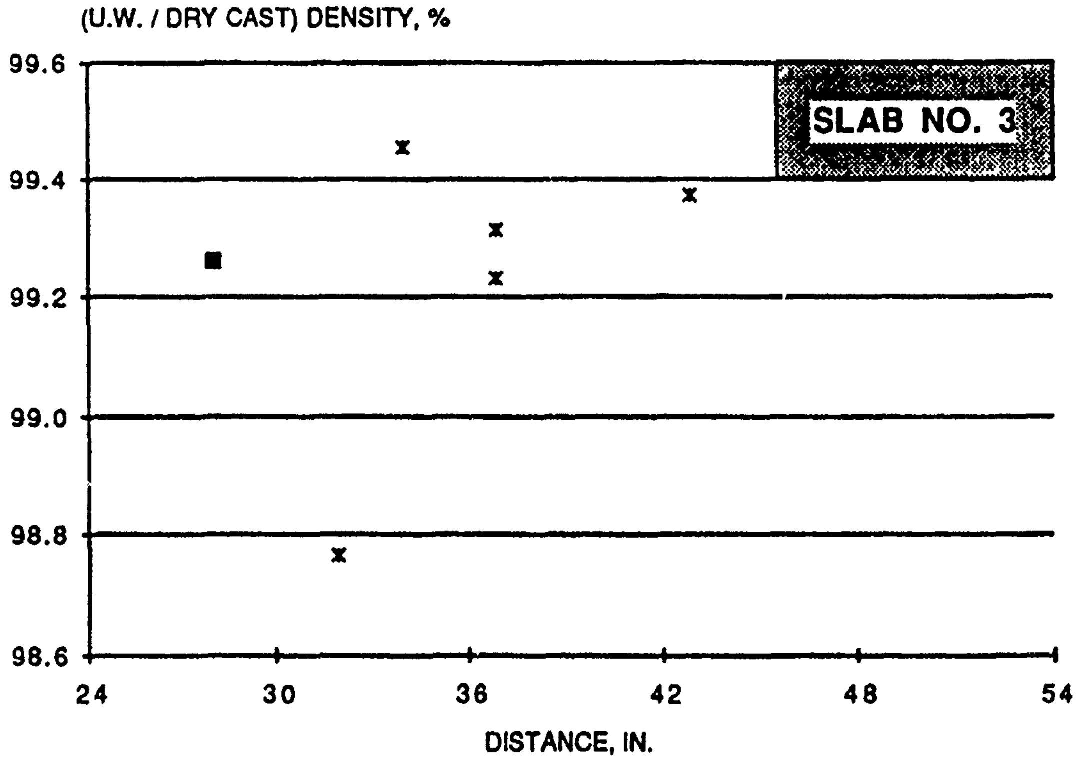


Fig. 79--Unit Weight along SLAB NO. 3

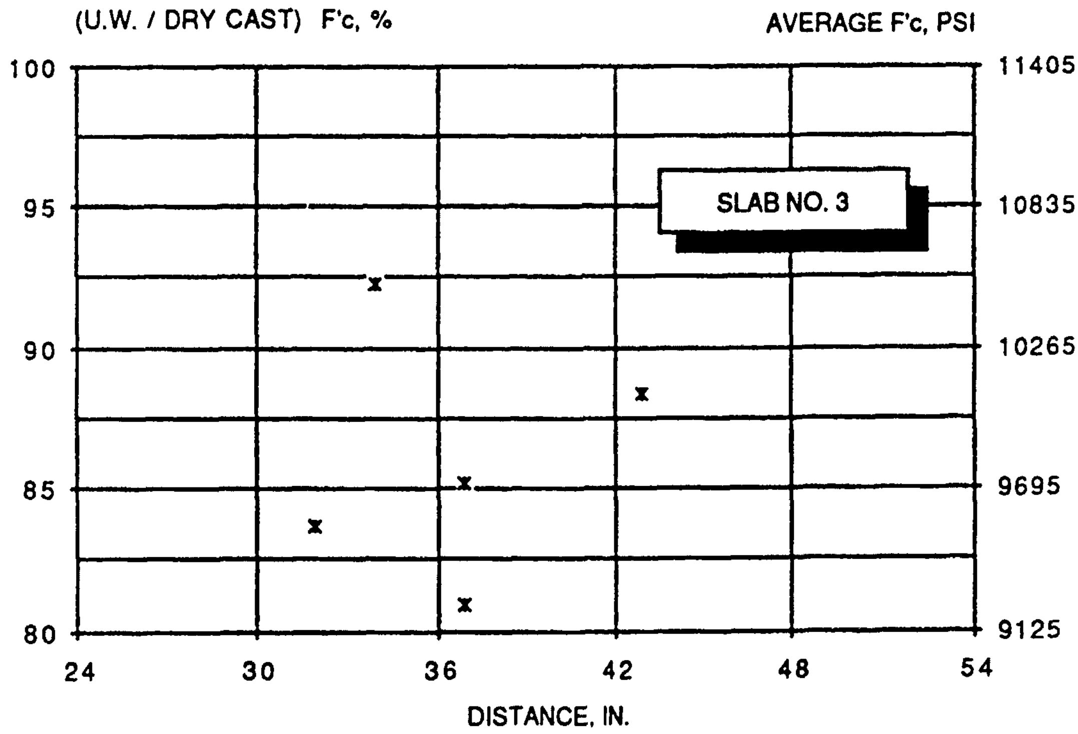


Fig. 80--Compressive Strength Values along SLAB NO. 3

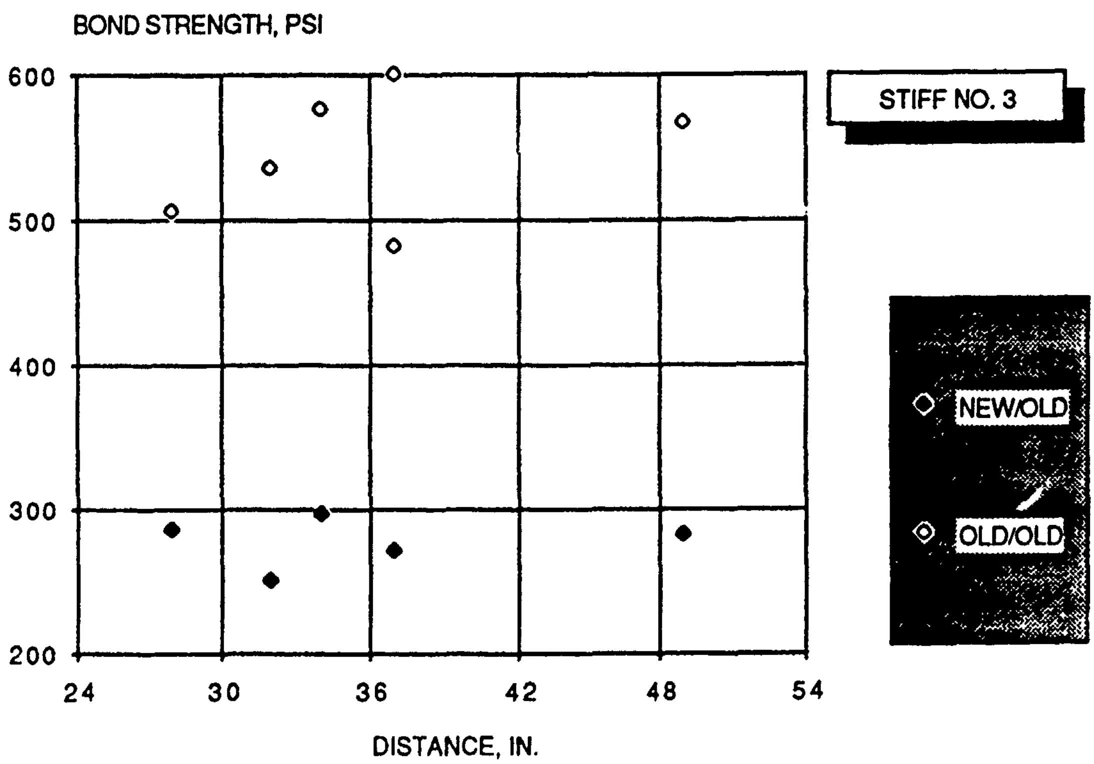


Fig. 81--Bond Strength Values along SLAB NO. 3

10.8 Comparison of Underwater-Compacted Slabs

Table 18 summarizes the main parameters and tested values of the three underwater-consolidated slabs. The necessary compaction effort seemed to decrease with the reduction in initial slab thickness. For example, a total of 26 passes were required to compact SLAB NO. 1 which measured 6.5 in. initially to 4.5 in. at the center. On the other hand, only three passes per lift were needed to reduce the depths of Lift A and Lift B of SLAB NO. 3 from 4 in. to 3.75 inches. The casting of thin concrete lifts seemed to reduce the mounding phenomenon observed at the center of SLAB NO. 1.

The placement and compaction of two lifts placed on top of one another, instead of a single thicker lift, seemed to facilitate the compactibility of the concrete for a given roller. For example, Lift A of SLAB NO. 2 was initially 1.5 x 1.5 ft and was spread to 4 x 1.75 ft after six passes. On the other hand, SLAB NO. 1 spread from 3 x 1.5 ft to only 4 x 2 ft after 26 passes.

In all three trials, the underwater processing secured in-place concrete densities similar to those of control specimens cast above water. The large number of passes of the first slab provided larger average densities than the other two trials. However, because of greater disturbance resulting from the large number of passes, SLAB NO. 1 had more loose materials at its top (higher cut/uncut density ratios).

The average in-place f'_c of all three slabs varied from approximately 9,400 to 10,200 psi, or 85 to 88 percent of the strength of specimens cast above water. SLAB NO. 2 had slightly higher f'_c than the other two slabs. The average bond strength to the underlying base slab varied from 275 to 285 psi for all three slabs. In general, SLAB NO. 3 can be considered to be the best among the three trial placements since it required the least compaction effort and provided smooth and high quality surfaces.

Table 18. Summary of Test Results

	SLAB NO. 1	SLAB NO. 2	SLAB NO. 3
COMPACTION, MED. ROLLER	2 PASSES	2 PASSES	0
, LARGE ROLLER	24 PASSES	4 PASSES	3 PASSES
LIFT A TO LIFT B	SIDE-BY-SIDE	BOTTOM AND TOP	BOTTOM AND TOP
INITIAL OVERLAY L x W, FT.	3 x 1.5	1.5 x 1.5	1.5 x 1.5
INITIAL DEPTH, IN. - LIFT A	6.5	5	3.75
- LIFT B	6.5	5	4
ROLLED L x W, FT - LIFT A	4 x 2	4 x 1.75	2.5 x 1.75
- LIFT B	- - -	2.5 x 2	2.5 x 1.75
AVG. DEPTH, IN. - CENTER	4.5	4.5	3.75
- QUARTERS	3.5	3.5	3.75
MAX. DENSITY, %	100.4	99.2	99.4
MIN. DENSITY, %	99.5	98.9	98.8
AVG. SLAB DENSITY %	99.8	99	99.2
CUT/UNCUT INCREASE, %	0.03 - 0.5	0.07 - 0.25	0.1 - 0.36
AVG. CUT/UNCUT INCREASE, %	0.23	0.16	0.18
MAX. F'c, %	86.4	93.7	92.1
MIN. F'c, %	80.7	84.6	80.8
AVG. SLAB F'c, %	85.1	88.3	86
, PSI	9405	10170	9805
BOND RANGE"NEW"/"OLD", PSI	260 - 295	235 - 345	250 - 295
AVG. BOND, PSI (# CORES)	285 (3)	280 (7)	275 (6)

10.9 Summary and Conclusions

Stiff concrete mixtures suitable for repairing thin damaged holes (less than one foot in depth) or for casting flat and wear-resistant overlays were developed. A total of eight trial mixtures were prepared to optimize mix proportions and evaluate alternative additives, including twisted steel fibers and short polyethylene fibers. The concrete was proportioned to be highly cohesive and highly resistant to water erosion and abrasion damage, yet plastic enough to minimize the required compaction effort.

Four promising concretes were selected, and several important properties were evaluated. The initial fluidity of the concrete was low, however, the concrete was still workable 90 min. after mixing. All concretes incorporated high concentrations of AWAs and had washout mass losses less than one percent after 10 test drops in water. The high

doses of AWAs and HRWRAs resulted in long delays in setting. The addition of $CaCl_2$ limited the initial setting times to less than 11 hours.

The average 28 day f'_c of the four concretes was 9,400 psi, and the 56 day flexural strength values ranged between 950 and 1,175 psi. Fiber-reinforced concretes developed higher splitting tensile strengths, ductility and strain capacity values than plain concretes. However, the f'_c and flexural strength values of the fibrous concretes were slightly lower than those of plain concretes.

The 72 hr. abrasion-erosion mass loss ranged between 2.1 and 2.5 percent for all concretes that were cast and consolidated above water and between 2.9 and 4 percent for all specimens cast and compacted under water. The 72 hr. abrasion mass loss of control non-fibrous concrete cast above water was 2.3 percent, comparing to 2.5 and 2.1 percent for similar concretes containing steel and polyethylene fibers, respectively. None of the tested concretes exhibited excessive temperature gains over time.

A small-scale experiment was conducted to determine the feasibility of under water compaction. Twelve slabs were cast by dropping loosely packed concrete measuring 12 x 12 x 3.5 in. through one foot of water. The concrete was compacted with a small concrete roller that was dragged over the fresh concrete. The number of compaction passes were varied from 4 to 16 times. The average thickness and relative density of the underwater-processed slabs were determined and compared to those compacted with the same roller above water. The exercise proved that less compaction was required when the concrete was submerged in water. The relative density of underwater-compacted concrete seemed to drop 0.5 to 1 percent after four passes. However, this reduction decreased as the number of compaction passes increased and reached approximately zero after 16 passes.

In the third phase of this chapter, a promising plain concrete (STIFF-M.B.) was cast in a large placement box in the laboratory, then spread and compacted in place using medium and large concrete rollers. This work was carried out to optimize initial lift thicknesses and compaction efforts that are capable of securing flat and durable repair

surfaces. A total of three slabs were tested where the initial lift thickness of an 18 x 18 in. concrete slab was varied from 3.75 to 6.5 in., and the total number of compaction passes ranged between 3 and 26. The in-place density, f'_c and bond strength to underlying concrete were evaluated. The experiment showed that the placement of two 4 in. thick concrete lifts placed on top of one another and compacted three times using a large concrete roller can secure a high quality slab measuring 3.75 in. in thickness. The average in-place density of this slab tested approximately 99 percent of the control concrete that was cast and vibrated above water. The average in-place f'_c was approximately 9,800 psi, and the bond strength to underlying concrete cast on land was 280 psi.

Based on the above findings, the following recommendations are presented:

A. The underwater casting and compaction of stiff concrete appears to be suitable for repairing shallow slabs under water since smooth and continuous surfaces can be secured without sizable reductions in density or thickness compared to concrete compacted above water.

B. The cementitious materials of stiff concrete should consist of 750 lb/yd^3 of cement and 115 lb/yd^3 of silica fume. The W/CM should be limited to 0.35, and a HRWRA should be used to reduce the W/CM.

C. AWAs should be incorporated to limit the washout weight loss to less than one percent after 10 test drops in water. A de-air admixture should also be added to minimize any entrapped air. An effective set accelerator can be used to control the stiffening rate of the concrete.

D. Hard natural pea gravel (3/8 in. MSA) should be used to enhance the wear resistance of the concrete and enable the casting of thin repair slabs. Proper steel fibers that can adhere to the cement matrix may be incorporated at low quantities to enhance the toughness and impact resistance of the concrete. The addition of fibers should not accelerate the wear damage of the concrete.

E. The abrasion weight reduction of dry-cast and underwater-cast concretes should not exceed 2.5 and 4 percent, respectively.

F. Stiff concrete, such as the STIFF-M.B. mixture, can be placed and packed above water in a bottom-dumping skip. The skip should then be covered and lowered gently in water over the repair area where it is discharged. The concrete may be allowed to fall a short distance through water. This drop should not exceed 15 inches.

G. The length and thickness of the cast slab should be small to reduce the required compaction. For example, fewer passes are necessary to compact a slab measuring 18 in. in length than a slab measuring 36 inches. Similarly, fewer compaction passes are needed to consolidate a 4 in. lift than a 6 in. lift.

H. A concrete slab measuring 18 in. long and 4 in. deep can be cast under water and compacted three times with a concrete drum measuring 2 ft in diameter. The roller can exert approximately 12 lb/in. net pressure under water. The final thickness of the compacted concrete can be approximately 2 inches. A thicker slab may be secured by casting a similar concrete lift over the first one and compacting it again three times to secure a flat 4 in. overlay.

I. Underwater-consolidated concrete can develop sound bonding to underlying concrete (280 psi). An in-place relative density of 99 percent of control density and f'_c in excess of 9,500 psi can be secured after 100 days of curing.

J. The casting and compaction of stiff concrete under water seems to offer an attractive alternative for the underwater repair of shallow scour holes and placement of wear resistant overlays over existing surfaces. Similarly, this new technique can enable the underwater construction of sloped surfaces. Trial placements similar to those described in this chapter should be carried out using the desired compacting device to optimize mix proportions and establish proper lift thicknesses and consolidation procedures.

CHAPTER ELEVEN

METHODOLOGIES AND RECOMMENDATIONS

11.0 Scope and Applicability of Recommendations

This chapter summarizes the findings of the previous chapters and offers guidelines which can assist engineers and constructors in planning for underwater repairs. Among these guidelines are means of cleaning damaged surfaces and reinforcing steel, installing dowel bars, selecting proper concrete-making materials and test methods, choosing concretes and compatible placement methods to repair deep (more than 3 ft), relatively shallow (1 to 3 ft deep) and shallow (less than one foot) scour holes under water.

Detailed methodology is presented for casting fluid concrete under water using the tremie and inclined tremie methods and for the placement and underwater roller compaction of stiff concretes. Other modified (proprietary) placement techniques are described in Chapter Three. Recommendations concerning testing procedures, mix proportions material selection and achievable properties are primarily based on the extensive experimental information compiled in this study.

The use of the developed concretes and placement techniques can be extended to applications other than the underwater repair of wear-damaged surfaces. Among these applications are the placement of concrete underwater to construct cofferdam seals, footings for bridge piers, b[illegible]-pier foundations of offshore structures and underwater canal linings.

11.1 Preparation of Damaged Surfaces

11.1.1 Removal of Debris and Deteriorated Concrete Wear-damaged concrete is usually eroded away, while the remaining concrete may still be intact. Scour holes may be filled with a variety of waterborne debris such as broken concrete, reinforcing steel, sand and

silt. The removal of all loose debris and remaining distressed concrete are vital steps for ensuring successful and lasting repairs. In certain cases, there may even be a need to remove undamaged concrete as well. For example, if a repair area is not deep enough to secure good bonding to the underlying materials, some of the base material may have to be removed.

11.1.2 Debris Removal Equipment A wide range of equipment that is normally employed on land can be modified for underwater utilization to remove both sound and deteriorated concrete, as well as waterborne debris and sediments. The type of debris, access, allowed time and budget of the repair normally determine the type of system to be used. Debris removal techniques can include any combination of water jetting, air lifting, grit-blasting, chipping, clam shell or drag line buckets. The selected system should be safe and economical and should not caused additional distress to sound surfaces.

High-pressure water jets, remotely-controlled or operated by divers, can be used to remove damaged or sound concrete, or to cut grooves and roughen cleaned surfaces in order to enhance the bonding to the repair overlay. A retrojet-equipped nozzle, which provides a reacting thrust force in the opposite direction of the main nozzle, can facilitate the handling of the device and increase the productivity of the work. Ultra-high pressure pulse jets can be used to cut small edges around the perimeter of excavated areas to prevent feathering at the edges. Abrasive additives may be used with such jets to improve their cutting abilities. High-pressure water jetting cannot cut reinforced steel and may be very slow when used on a highly wear-resistant concrete. Fan jet nozzles can be employed to remove fouling and marine organisms from repair surfaces. The optimum distance from the concrete surface for the fan jet nozzles and the colliding angle of the jet were found to be 0.5 to 3 in. and 40 to 90 degrees, respectively (ACI 546.1 1988).

A land-based water blasting device has been developed for removing deteriorated concrete bridge decks. The device provides a high-pressure water jet which travels back

and forth on a horizontal bar located at the front of the machine. The water jet is claimed to operate at 17,000 psi and can make a 3 to 5 in. groove in the concrete and was reported to be capable of cleaning 2,000 ft^2 of concrete within 24 hrs. without damaging reinforcing steel (Wallace 1985). It has been proposed to mount this device on a remote-controlled robot with attached TV cameras for underwater use.

Hard concrete edges can be cleaned by pneumatic or hydraulic saws or grinders that can operate in water of any depth. Vehicle-mounted pneumatic powered chipping hammers supplied with TV cameras can be used to chip concrete under water. A rotary head cutter can be fitted to a backhoe excavator and used to cut concrete into small and easy to handle pieces (Engineer Manual 1986), which can then be removed with a clamshell bucket. A conventional suction dredger can be employed to suck large volumes of loose sediments that may be deposited in big scour holes. The dredger should be combined with water jetting to place fines into suspension and facilitate their removal.

11.1.3 Cleaning Repair Surfaces Wear-damaged surfaces are normally smooth in texture, therefore, they should be roughened to enhance bonding to repair concrete. This can be done using light impact tools or high-pressure water jetting. Loose bonding between damaged surfaces and repair concrete can lead to spalling and accelerated deterioration. Therefore, once the damaged concrete and debris have been removed, obstacles such as sediments, laitance, organic materials and marine growth which can prevent the development of sound bonds should be cleared.

The underwater placement of concrete should proceed promptly after cleaning the repair surface, especially in areas of high sedimentation or active marine growth. Providing that proper surface preparation is achieved, the developed concrete mixtures should soundly adhere to the repair surface without the need for using bonding agents.

11.1.4 Rehabilitation of Existing Steel After removing damaged concrete, the exposed surface of reinforcing steel, structural steel columns or dowel bars should be properly

cleaned. Such measures are essential to ensure good bonding to the repair concrete and preserve the overall structural behavior of the reinforced slab. Ru·· deposits and other harmful materials can be cleaned using wire brushes or high-pressure water jets.

Whenever a significant reduction in the cross-sectional area of reinforcing steel has occurred, additional reinforcement should be provided. The existing steel can be cut and replaced by new reinforcement. Twisted and damaged bars should also be replaced. New bars can be spliced to existing steel: the use of small diameter bars can reduce the required overlapping length. In areas where concrete cannot be chipped for splicing new bars, adequate mechanical splices may be employed.

11.2 Steel Installation

11.2.1 Detailing Reinforcing Steel Whenever a repair area needs to be reinforced, the steel cage can be assembled in the dry, then lowered in water and guided into placed with the help of divers. Proper measures must be taken to ensure that sound concrete can reach and completely surround the steel bars. For example, enough spacing should be provided between steel bars (12 in. typical) to reduce the interference with concrete flow. Whenever reinforced concrete slabs are cast under water, the concrete should be highly fluid to spread readily around the bars. In addition, it is essential that the concrete placement proceeds without interruptions in order to keep the concrete mobile.

11.2.2 Installation of Dowel Bars Large differences in the modulus of elasticity or coefficient of thermal expansion between the repair concrete and surrounding materials can result in high differential strains at their interface. Such strains can cause tensile stresses which have to be partially resisted by the available bonding betwe·n the two materials. High shear forces caused by the impact of waterborne debris or uplift pressures resulting from high-velocity water flow can add to the tensile stresses at the interface between the

two materials. Therefore, dowel bars may be required to anchor the repair concrete to underlying concrete or bed-rock.

The size and distribution of anchor bars depend on the expected differential stresses, the shear and uplifting forces and the available bond strength between the cast overlay and base materials. A typical arrangement may consist of placing No. 6 bars at intervals of 6 ft in both directions. In extreme cases, dowel bars can be sized to resist the total uplift and shear stresses without accounting for the available bond strength. Large prestressed rock anchor bars can be used in high-head dam stilling basins. Whenever thin concrete lifts are cast, the dowel bars should be bent in hook shapes at the top to develop proper anchorage. Headed dowel bars may also be employed.

One often-used, although labor intensive, operation involves the drilling of holes under water, into which dowel bars or rock bolts are then inserted and bonded using either a cement or epoxy grout. A prepackaged plastic cartridge containing a two-component epoxy mixture can be fitted in the drilled hole where a dowel bar is then inserted and twisted to break the cartridge and mix the epoxy grout. Another approach is to place a large number of small dowels percussively under water.

11.3 Finalizing Concrete Mixtures - Properties and Test Methods

Concrete intended for underwater repairs should be tailored to satisfy various properties which have direct bearing on the finished surface and durability of the repair. This section highlights these properties and describes proper laboratory tests that can be used to evaluate the effectiveness and compatibility of different materials and qualify promising concretes for actual repairs. Guidelines for proportioning concrete mixtures suitable for repairing deep, relatively shallow and shallow scour holes under water are presented in sections 11.10, 11.8 and 11.11, respectively.

11.3.1 Mobility and Fluidity Retention Adequate fluidity should be provided to facilitate the handling, casting, underwater spreading and consolidation of concrete. The required initial fluidity depends on the adopted placement technique and water movements. For example, the fluidity of concrete intended to repair large and deep scour holes should be high to facilitate spreading, self-leveling and self-compacting. On the other hand, the fluidity of stiff concrete intended to repair shallow scour holes is not critical since the concrete is spread and compacted in place. Instead, the washout resistance of this stiff concrete must be high in order to minimize its propensity to intermix with water while being processed under water. Positive measures should be taken to ensure high mobility at the expected service temperature. Sharp fluidity losses should be avoided until the concrete is cast and processed in place.

The fluidity retention of fresh concrete can be monitored using the slump or DIN flow table tests. The latter test is useful to assess the mobility of fluid concrete that is subjected to external dynamic forces, such as large hydrostatic forces resulting from deep placements. The determination of the height of the concrete and its base diameter at the conclusion of the slump test can provide good indications of its fluidity under quasi-static conditions. In performing the slump or flow tests on concretes containing AWAs, the measurements should be delayed for one minute until the plastic flow of the concrete stops.

The slump or flow tests can be used in the field to monitor the fluidity of the delivered concrete. However, neither test can reflect the ability of fresh concrete to spread and form flat surfaces under water. Therefore, when finalizing repair concrete in the laboratory, the underwater leveling test (section 5.1.3) should be used to assess the spreadability of fluid concrete under water.

11.3.2 Cohesiveness It is essential to maintain proper aggregate dispersion within the concrete mass (especially at the top surface of the repair slab) to ensure proper abrasion resistance. Bleeding should be minimized to prevent the formation of laitance and to avoid

the weakening of the transition zone between the hardened cement paste and aggregate which can reduce the abrasion resistance. Excessive bleeding is also detrimental to sound bond development between the concrete and surrounding surfaces, subsequent concrete lifts and reinforcing steel.

The tests for measuring segregation susceptibility and bleeding can be used to compare the stability of different concretes. The former test (sections 5.14) measures the ability of fresh concrete to resist scattering and separation when dropped in air and through water. The separation of aggregate from concrete provides an indication of the homogeneity of the fresh concrete. The test also evaluates the propensity of the concrete to segregate due to the reduction of cohesive strength caused by water erosion. The susceptibility to bleeding of different concretes can be determined using the test described in section 5.16.

11.3.3 Washout Resistance Part of the cementitious materials and other fines can be washed out into suspension as fresh concrete comes into contact with water. Water erosion can dramatically impair the durability of repair surfaces. A balance between the fluidity and washout resistance should be maintained. For example, concrete used to repair relatively shallow scour holes may have to be dropped in water. Such concrete should resist water dilution, yet it should be fluid enough to spread and self-compact.

The differential velocity between fresh concrete and surrounding water should be reduced. For example, concrete can be gently placed under water using an inclined tremie pipe instead of a vertical pipe. Furthermore, the water velocity at the placement site should be reduced until the initial setting of concrete has occurred (as discussed in section 11.13).

The relative resistance of concrete to water erosion can be evaluated using the washout test (section 5.1.5). The cumulative washout weight reduction of fresh concrete can be determined for fluid and stiff concretes by dropping a concrete sample 3 and 10 times, respectively, in a column of water with a constant depth.

11.3.4 Stiffening, Heat Generation and Water Contamination Concrete should set soon after placement and processing to reduce the risk of water erosion. However, when several lifts are to be cast, the initial setting should be delayed long enough until subsequent concrete lifts have been cast over it to avoid formation of cold joints. The stiffening rate of the selected concrete should be determined at a temperature similar to that of the water at the repair site. If the setting time is excessively delayed, proper set accelerators can be added to the concrete, providing that they do not critically affect the fluidity and durability of the concrete. Otherwise, the repair site should be protected from fast flowing water. The setting time can be measured using the Proctor Penetration test (section 5.1.6).

Concrete should be proportioned to reduce the heat of hydration. Temperature-related problems can be reduced by replacing part of the cement by pozzolan and pre-cooling the concrete. This is especially valuable in repairing large and deep holes.

The turbidity and contamination of surrounding water should be minimized when concrete is cast in water. Effective types and doses of AWAs can be determined when finalizing concrete mixtures by measuring the pH and turbidity of the water after pouring a fixed amount of fresh concrete through it (section 5.16).

11.3.5 Abrasion Resistance The underwater repair surface must be resistant to abrasion damage in order to reduce the frequency of repairs. In proportioning concrete mixtures, hard aggregate and strong cement matrix should be provided, and good bonding between the hydrated cement paste and the aggregate should be secured (section 4.2.1). Furthermore, the concrete should resist bleeding, segregation and water erosion. The underwater abrasion test (section 5.2.1) can be used to compare the wear resistance of prospective repair concretes that are cast above and under water.

11.3.6 Strength Underwater-cast concrete should develop sound mechanical properties similar to those that can be attained when it is cast and consolidated on land. Furthermore, the modulus of elasticity and coefficient of thermal expansion of the repair concrete should

be compatible to those of existing materials in order to reduce differential tensile stresses at their interface. Prospective concrete mixtures can be cast in a box filled with water. Cores can then be taken from the hardened slab to investigate in-place properties and compare them to similar values of concrete cast and consolidated above water.

11.3.7 Bond Development Proper adhesion to various repair surfaces is essential to secure durable repairs. Several measures that can enhance the strength of the cement paste, minimize water erosion and bleeding can enhance adhesion. The ability of underwater-cast concrete to bond to existing concrete can be investigated by casting concrete in a box filled with water which has a hardened base slab. Cores are then taken through both concretes to test the point-load tensile strength at their interface (section 5.2.3) in order to evaluate the bond strength.

The adherence of concrete to reinforcing steel can be evaluated by casting concrete under water in a standard mold containing a reinforcing bar, then testing the pullout strength between the steel and the hardened concrete (section 5.2.3). Similar tests can be done for the same concrete that is cast and consolidated on land. The pullout test is useful for evaluating effective admixtures which can enhance the bonding of concrete to reinforcing steel and secure similar values to those obtained with concrete cast above water.

11.4 Selection of Concrete Making Materials and Additives

Concrete constituents should be carefully selected to meet the various required critical properties presented in the previous section. The suitability and compatibility of these materials should be verified when finalizing concrete mixtures.

11.4.1 Aggregate Aggregate should be sound and free of any harmful substances that can hinder the durability of the concrete. The hardest available aggregate should be employed to enhance abrasion resistance. Well graded, rounded gravel containing minimal amounts of flattish or flaky particles should be used to reduce the water demand, enhance

the workability and improve the quality of the transition zone between the aggregate and hardened cement paste. It is recommended to use coarse aggregate with maximum size of 3/8 to 3/4 inches.

Fine aggregate should consist of hard sand or crushed stone free of dust and other impurities. A high sand content (42 to 50 percent of total aggregate volume) is recommended to improve the cohesiveness and washout resistance of the concrete. Fine cementitious materials, such as fly ash or silica fume, can be added to compensate for any lack of fines.

11.4.2 Cementitious Materials The cement content required for underwater applications should not exceed the amount desired to achieve the needed strength and abrasion resistance. Approximate cement contents of 600 and 750 lb/yd^3 were found to be adequate for fluid and stiff concretes, respectively. A Type II cement is recommended because of its moderate heat generation, sulfate resistance, setting time and rate of strength gain. Whenever concrete comes into contact with water containing soluble and aggressive substances, such as sulfates, a Type V cement with pozzolan or a blast furnace slag cement can be used.

Silica fume should be added to enhance the wear resistance and adhesion to repair surfaces and reinforcing steel. Depending on the amount of AWA in use, silica fume can be added as 5 to 15 percent of the cement weight. Fly ash can replace part of the cement to reduce temperature related problems, or it can be added to enhance the workability of concrete containing silica fume.

11.4.3 AWAs and HRWRAs AWAs should be incorporated to improve the washout resistance and cohesiveness of the fresh concrete and enhance the in-place mechanical properties and durability of the hardened concrete. AWAs can reduce bleeding and laitance, thus enhancing the ability to bond to surrounding surfaces. The content of AWAs depends on the required washout resistance, which is a function of the concrete exposure to

moving water. High concentrations of AWAs are necessary when concrete is spread and compacted under water or cast in fast flowing water or surf.

The incorporation of AWAs decreases the workability of fresh concrete. Hence, a HRWRA should be used to restore the required fluidity without the need to add more water. The selected HRWRA should not result in sharp fluidity losses. A high dose of a conventional WRA may substitute the HRWRA when the W/CM is high and the added dose of AWA is low.

The effectiveness and compatibility of AWAs with other additives, especially HRWRAs, should be verified. The combination of high dose of HRWRA and AWA may result in excessive delays in setting (in excess of 10 hours). Therefore, proper measures should be taken to control the setting time (if necessary). De-airing additives should be used to de-foam entrapped air caused by certain types of AWAs (cellulose-based AWAs).

11.5 Mixing Sequence of Concrete

Concrete mixtures suitable for underwater repairs may contain several additives. Proper care should be taken to ensure thorough dispersion of the various admixtures to secure their intended benefits. Liquid admixtures, such as HRWRAs and AEAs, should be added separately, preferably diluted with some of the mixing water. The AWA can best be added in a pre-hydrated form with water. Such practice can eliminate the formation of dry lumps of AWA, thus improving the effectiveness of the additive. Thickening additives, such as silica fume and AWA should be introduced to the mixer after the addition of mixing water and HRWRA to facilitate their dispersion. Whenever fibers are incorporated (stiff concrete) they should be added last to the wet concrete.

While the concrete can be mixed in a transit mixer, it is best to use a high-shear mixer to thoroughly disperse the concrete and reduce the formation of dry lumps. The concrete should be mixed until uniformly blended concrete is obtained, but not so long as to produce excessive generation of heat or loss in fluidity. Depending on the transporting

time and temperature conditions, part of the HRWRA can be added at the site prior to placement. Fluid concrete containing an AWA should not present additional difficulties in cleaning mixers, pump lines and other concrete handling devices. On the other hand, the cleaning process is more time consuming when the concrete is stiff than that of conventional concrete. Therefore, cleaning should be done soon after usage, before the concrete starts to set.

11.6 Monitoring Concrete Properties Prior to Placement

Although the final concrete mixture is designed to meet the various characteristics listed in section 11.3, several tests still need to be performed at the job site prior to casting. These consist of monitoring the flow or slump values, washout resistance and unit weight of the delivered concrete. Moreover, at least nine concrete cylinders should be prepared for subsequent testing of f'_c at 7, 28 and 56 days. These tests should be carried out by qualified operators.

11.7 Transferring Concrete to Placement Devices

Freshly-mixed stiff concrete can be deposited directly from the mixer into the placement device (skip or bucket). On the other hand, fluid concrete can be transferred from the mixer to the placement device by pumps or conveyor belts.

Downhill pumping of concrete should be avoided, since it may lead to segregation and plug formation. It is best to use the pump for horizontal transfer and gravity feed for the downward flow. The pumpability of the concrete should be checked before actual field use, since high pumping pressure may force water into coarse aggregate causing stiffening, and hence increasing the necessary pumping pressure. Moreover, high pressure can compress entrained air bubbles within the concrete and may cause the entrapment of air pockets.

11.8 The Repair of Small and Relatively Shallow Scour Holes

11.8.1 Applicability Presented in this section are guidelines for proportioning and casting fluid concretes that are suitable for repairing small and relatively shallow (1 to 3 ft deep) scour holes under water. The limited depth of such repair areas and the need to frequently move the placement device through water to repair neighboring holes makes it difficult to maintain a continuous seal at the bottom of the device. Moreover, concrete is placed in small volumes, thus limiting the hydrostatic head which otherwise would tend to consolidate and remix freshly-deposited concrete.

11.8.2 Suitable Concrete Mixtures Mix proportions and properties of fluid concretes suitable for such repairs can be summarized as follows:

A. The cementitious materials may consist of 600 lb/yd^3 of cement, 40 lb/yd^3 of silica fume and 30 lb/yd^3 of fly ash. Suitable W/CMs can range between 0.40 to 0.42, although the lower value is preferred.

B. A high sand content (46 $\pm$ 2 percent of the total aggregate volume) should be used. A hard natural pea gravel with nominal size of 3/8 in. is recommended for the coarse aggregate.

C. The washout weight loss of such concrete should be limited to 3 percent after three test drops in water. An AWA should be incorporated at a medium dose. Approximate concentrations of the Protex, Kelco, Master Builders and Rescon AWAs (expressed in percent of the weight of cementitious materials) can be 0.35, 0.28, 0.85 and 2.50 percent, respectively.

D. Cellulose-based AWAs may entrap excessive air, therefore, a de-airing additive should be used. A 3 to 5 percent air content may be allowed to improve the rheological properties of the fresh concrete and enhance the freeze-thaw durability (when needed).

E. Approximate initial slump and flow values of 10 and 21 in., respectively, are recommended. The concrete should incorporate an effective HRWRA that is compatible with the other additives. It is desired to limit the slump and flow losses which can be monitored for 2 hrs. after the end of mixing to 30 percent of initial fluidity values. Once cast in water, the fresh concrete should flow readily and attain moderately flat surfaces free of laitance.

F. The incorporation of high doses of AWAs and HRWRAs may lead to long delays in setting times. An effective accelerator can be incorporated to control the setting time (if needed).

G. Abrasion-erosion weight losses of dry-cast and underwater-cast concretes should not exceed 3.5 and 5 percent, respectively, after 72 hrs. of testing.

11.8.3 Placement Methods Several of the existing and underwater placement methods (Chapter Three) were originally developed for massive underwater placements of thick slabs where the bottom of the placement device can be properly embedded within freshly-cast concrete. However, due to the limited depth of relatively shallow (1 to 3 ft deep) scour holes, concrete may have to be dropped a short distance in water. Therefore, in addition to using washout-resistant concrete, the differential velocity at the interface between the fresh concrete and the surrounding water should be reduced to decrease water erosion. This can be achieved by casting concrete through an inclined tremie pipe which results in lowing the kinetic energy of the discharged material, thus minimizing water dilution and laitance formation.

The reduced concrete velocity should not significantly affect the spreadability of the concrete since the material is fluid in nature, and the distance that the concrete needs to flow to fill the relatively small scour holes is limited. It is believed that the slanted position of the pipe enables some of the entrapped air in fresh concrete and air pockets trapped inside the pipe during casting to rise to the top section of the pipe and bleed outward. As a result,

the disturbance to freshly-cast concrete that might result from the rising air bubbles within the fresh concrete could be reduced.

As demonstrated in Chapter Eight, concrete cast with an inclined tremie pipe can yield higher in-place density and strength values and lower laitance than identical concrete cast under water using a vertical tremie pipe. The use of an inclined pipe proved very effective with a marginal concrete possessing a relatively low washout resistance.

It was demonstrated in Chapter Eight that properly designed and cast concrete can flow readily under water and secure in-place f'_c values that can range between 8,000 and 10,000 psi and average relative density values as high as 99 percent of control specimens cast and consolidated above water. The concrete can develop bond strengths as high as 380 psi to damaged surfaces. It was also shown that consecutive concrete lifts placed approximately one hour apart can bond well together (up to 510 psi) without the need to remove any settled materials deposited over the lower lift surface.

As presented in section 8.15, properly designed concrete cast under water with a 45^0 inclined tremie pipe to fill a rough-edged hole (11 x 2.5 x 2.5 ft) flowed well without exhibiting significant reduction in quality. The resultant surface slope was 1:35, and the average tested in-place density and f'_c values over the entire repair slab were as high as 98 and 88 percent, respectively, of control specimens cast above water.

11.9 Inclined Tremie Operations

<u>11.9.1 Pipe Description</u> As with conventional tremie operations the pipe can consist of steel tubular sections that are bolted together using a gasket at each joint to prevent leakage. A hopper should be attached to the top of the pipe to facilitate the transferral of concrete. The pipe diameter should be large enough to minimize interference with the flow. Typical pipe diameters can range between 6 and 10 inches. The interior of the pipe should be free of any intrusions (such as weld beads) which can interfere with the concrete flow causing turbulence and arching of the aggregate against the inner wall which can result in

subsequent plugging. Similarly, the pipe should be straight all the way to prevent any turbulence and jamming.

Although successful results have been obtained with tremie pipes placed at 45^0, the desired angle depends primarily upon the available clearance, depth and water movements. A simple means of measuring the inclination angle of the pipe should be employed. The pipe should be marked on the outside, and a chart should be provided to determine the depth of the discharge point from the surface of the water for various inclination angles.

The pipe can be supported from a crane, or it can be mounted on a special stinger attached to a barge. The pipe should be rigid to withstand handling stresses. The barge can travel slowly to relocate the bottom of the pipe to neighboring damaged areas. The positioning of the pipe end can be controlled by divers or with the help of TV cameras.

11.9.2 Pipe Lubrication and Sealing The pipe can be initially lubricated using water, bentonite or a rich cement mortar in order to decrease the initial friction between the concrete and the pipe wall. The bottom of the pipe can then be sealed with a rubber-gasketed wooden or steel plate that is slightly larger than the pipe diameter. The plate is attached to the pipe with a heavy wire that can extend to the top of the pipe to facilitate its cutting, unless another proven system is employed to cut or break the wire.

In shallow water (less than 20 ft), a ball with a slightly smaller diameter than that of the pipe can be employed to initiate a placement. Approximately 2 ft of highly cohesive concrete can be charged behind the ball ahead of the repair concrete to minimize seepage of water around the ball, thus protecting the charged repair concrete from water dilution.

11.9.3 Starting the Placement The end of the pipe should be positioned at the low end of the damaged area. The distance between the end of the pipe and the repair surface should be minimized to reduce the initial free-fall of concrete through water. It is desired to place the mouth of the pipe close to the edge of the repair hole to limit the back flow of

the concrete behind the discharge location where segregated concrete may be deposited, as shown in Chapters Eight and Nine.

Once in place, the pipe should be filled with concrete to the desired elevation, then the side wires supporting the end plate should be cut to remove the end cap and commence the placement. The feeding of concrete should proceed without interruptions to maintain sufficient kinetic energy needed to overcome the internal shear resistance of the concrete and the external friction of various obstacles, thus allowing the concrete to spread and self-level. In repairing long holes, inclined tremie pipes can be spaced as far as 15 ft apart.

11.9.4 Moving the Pipe During Placement The pipe should be held stationary while concrete is being cast at a single location. Whenever possible, the bottom of the pipe should be embedded in freshly-cast concrete. A flexible tubing tightly attached to the bottom of the inclined pipe can be manipulated by a diver to direct the discharge of concrete to fill closely-spaced scour holes.

As demonstrated in Chapter Eight, the underwater discharge of concrete through an inclined tremie pipe can proceed successfully while the pipe is being moved through water to repair closely-spaced scour holes. Positive measures should be taken to keep the pipe filled with concrete while the pipe is being moved in water to prevent water from entering the pipe and eroding the concrete inside. The pipe end should be kept as close as practical to the bottom slab.

If neighboring damaged areas are not closely spaced together, it is best to recover the tremie pipe above water and seal it again for the next placement. Another alternative is to use a pneumatic or hydraulic shut off valve which can close the pipe before relocating it in water to repair other areas. A properly designed shut off valve can prevent the concrete from falling through water and the water from entering the pipe and washing out fresh concrete. In fabricating such a valve, a positive effort should be taken to prevent clogging

or bridging of the aggregate or leakage of the mortar, or any interference with the flow of the cast concrete. The valve should be self-clearing and easy to operate from above water.

11.9.5 Resealing the Pipe In case a reliable foot valve is not available, the tremie pipe can be retrieved from water to start a dry placement (section 11.9.2). Another alternative is to keep the pipe submerged over the new repair area and use a polystyrene or rubber plug ahead of the concrete to displace the water, thus minimizing the intermixing of concrete with water. This method of restarting concrete placement is not recommended at locations where concrete was recently cast since the displaced water rushing down the tube can erode the freshly-deposited concrete.

11.9.6 Dropping Concrete Through Water The free-fall of concrete through water should be minimized to reduce water erosion and secure abrasion-resistant surfaces. This is especially important when the concrete is highly fluid. Free-fall distances from 6 to 12 in. may be allowable in repairing relatively shallow scour holes but should be avoided whenever possible. Excessive drops in water can be detrimental to the quality of repair surfaces. For example, it was demonstrated in Chapter Eight that a fluid and washout-resistant concrete may suffer 10 and 65 percent reductions in relative density and f'_c, respectively, if permitted to fall 2 ft in water. Whenever concrete is accidentally dropped a large distance in water, it is recommended to discontinue the placement and remove the segregated materials by jetting and air-lifting.

11.10 The Repair of Reinforced Slabs or Deep Scour Holes

11.10.1 Applicability The recommendations offered in this section are suitable for highly fluid concretes that can be used for casting reinforced slabs and beams or for filling large and deep (more than 3 ft) scour holes under water. In repairing deep scour holes, highly fluid concrete may not develop high resistance to abrasion-erosion. Therefore, an

overlay of a more wear-resistant concrete (section 11.8.2 or 11.11.2) may be provided over the repair surface, if needed.

11.10.2 Concrete Mixtures Mix proportions and properties of highly fluid concrete suitable for casting reinforced slabs or beams and filling deep and large scour holes under water are as follows:

A. The cement and silica fume contents should be 600 and 40 lb/yd^3, respectively. A 30 lb/yd^3 fly ash can be added to enhance the consistency of the silica fume concrete. Because of the nature of concrete-making materials and additives used in this research, high W/CMs (0.45 to 0.48) were necessary to ensure high fluidity. However, it is desirable to employ more powerful HRWRAs or modify the mix proportions to lower these W/CMs.

B. Approximate initial slump and flow values of 11 and 28 in., respectively, are desired to secure proper flow around reinforcing steel and result in flat surfaces. The concrete should incorporate a high dosage of HRWRA. Sharp fluidity losses and long delays in setting times should be prevented.

C. A high sand content (approximately 44 to 48 percent of the total aggregate volume) and small-sized natural gravel are recommended.

D. The washout weight loss should be limited to 10 percent after three test drops in water. A low dose of AWA should be used to reduce the internal shear resistance of the fresh concrete and enable it to spread readily. Approximate concentrations of the Protex, Kelco and Master Builders AWAs can be 0.12, 0.10 and 0.30 percent, respectively, of the weight of cementitious materials.

E. De-airing additives should be incorporated if excessive air is entrapped. Adequate air volume may be provided to improve the rheological properties or enhance the freeze-thaw durability (if necessary).

F. The 72 hr. abrasion weight loss of dry-cast concrete should not exceed 5 percent, unless the deep repair area is to be covered with a more wear-resistant concrete.

11.10.3 Placement Methods Large scour holes and reinforced members may be deep enough to allow the bottom of the placement device to be inserted into freshly-cast concrete, thus reducing the risk of water erosion and segregation. Conventional and proprietary methods normally used for casting deep and massive concrete under water can be used. Several of these techniques were discused in Chapter Three.

It is recommended to avoid pumping concrete downward in repair operations. Pumped concrete is usually placed in surges, therefore, the jerking action which results can disturb freshly-cast concrete and increase the risk of water erosion. Furthermore, it is possible for concrete pumped downward to fall faster than the driving action provided by pumping. Therefore, air pockets and a vacuum can be created within the pump line leading to segregation. Although this problem may sometimes be solved by installing air release valves at the top of the pump line, the risk of segregation and subsequent plugging of the pump line and interruption of construction operations are still high.

It is recommended to use the inclined tremie or the conventional tremie methods to fill large and deep scour holes or cast reinforced slabs under water. In shallow placements (less than 30 ft) it may be possible to fill most of the pipe with concrete to ensure continuous concrete discharge. However, in deeper placements, the pipe should be filled approximately half of the vertical distance between the bottom of the pipe and the water surface. This is important to provide a concrete surcharge pressure that is slightly higher than the hydrostatic pressure at the bottom of the pipe. Such practice is necessary to secure slow, steady and regulated discharge of concrete under water. A high differential pressure increases the velocity of the cast concrete, thus increasing the risk of water dilution, segregation and disturbance to freshly-cast concrete. On the other hand, very low

differential pressure may cause water to rush upward inside the pipe, hence washing out the fresh concrete there.

It is desirable to start the tremie placement dry by capping the bottom of the pipe prior to submerging it in water. The cap may consist of a rubber-gasketed wooden or steel plate that is attached to the bottom of the pipe with a light wire. The pipe is then lowered in water until its mouth is seated at the bottom of the casting area. The pipe is filled with concrete to the desired level, before lifting it approximately 6 in. to break the wire and start the casting (Gerwick et al. 1981). Concrete should be discharged continuously until a mound is formed around the bottom of the placement device. The end of the pipe should be kept immersed approximately 3 ft in freshly-cast concrete, whenever possible.

In repairing large scour holes, the spacing between discharge locations can be 15 to 20 feet. Uninterrupted discharge of concrete is necessary to maintain continuous movement of the concrete and secure flat surfaces. At the end of the placement, the bottom of the pipe should be retrieved slowly from the concrete to minimize any disturbance to existing repair surfaces. Prior to recovering the pipe from fresh concrete, the bottom of the pipe should be closed to prevent the fall of fresh concrete which is still inside the pipe into the water and over the repair area. A pneumatic or hydraulic shut off valve can be used to close the pipe. Another approach can be to send down a specially-designed closure plug that can latch into a recess to restrict further flow of concrete out of the pipe.

Highly fluid concrete suitable for repairing deep scour holes must be prevented from falling a large distance in water. As demonstrated in section 9.3.7, when such concrete was dropped 3 ft in water, it resulted in severe segregation and water erosion. On the other hand, superior results were obtained when the same concrete was used to cast a 22 x 10 x 1.3 ft slab under water with an inclined tremie pipe initially dropped 9 in. in water. The concrete spread readily from the discharge location and developed smooth and very flat surfaces (1:190 slope). The average in-place relative density and f'_c values were as high as 99 and 95 percent, respectively.

The same concrete was used to cast a moderately congested reinforced beam measuring 11 x 2 x 2 feet. The steel cage consisted of No. 6 top and bottom bars spanning in three directions and spaced 12 in. apart. The concrete flowed readily around the cage and resulted in a smooth surface (1:90 slope). The concrete tested approximate relative in-place density and f'_c values of 100 and 94 percent, respectively (section 9.2).

11.11 The Repair of Shallow Scour Holes and Placement of Thin Overlays

11.11.1 Applicability Preliminary recommendations are presented for proportioning, casting and consolidating stiff concrete under water to patch shallow (less than one foot deep) and unreinforced scour holes. Such concrete is especially useful for casting concrete in relatively fast moving water or for constructing sloped surfaces under water, such as in canal lining. The concrete can also be used for casting flat and highly wear-resistant overlays to protect existing slabs or recently repaired surfaces. While other consolidation methods (vibrating screeds, vibrating plates, etc.) have been used on land, they are not thought suitable for underwater work due to their tendency to cause segregation. Hence, this section concentrates on roller compaction procedures.

11.11.2 Suitable Concrete Mixtures Guidelines for proportioning stiff concretes that can be delivered under water in closed skips or buckets and then spread and densified in place by rollers are as follows:

A. The cement and silica fume contents should consist of 750 and 115 lb/yd^3, respectively. The lowest practical W/CM should be used, but it should not exceed 0.35.

B. Hard pea gravel is recommended for the coarse aggregate. The volume of the gravel should be high to enhance abrasion resistance. Similarly, enough fines should be provided to enhance the plasticity of the concrete.

C. A high concentration of AWA should be incorporated to limit the washout weight loss to one percent after 10 test drops in water. Typical doses of the Protex, Master Builders and Kelco AWA products can be 0.75, 1.75 and 0.50 percent of the total weight of cementitious materials. A de-airing additive should be used to de-foam entrapped air.

D. A compatible HRWRA should be used to minimize the water demand. Typical initial slump and flow values can be as low as 2 and 11 in., respectively. Positive slump values should be retained until the material is processed in place. The initial setting time should be delayed until successive layers of concrete have been consolidated. The concrete should set soon thereafter to reduce the risk of water erosion.

E. A small volume of steel fibers that can bond well to the cement paste can significantly improve the toughness of the concrete without adversely affecting its abrasion resistance, as demonstrated in Chapter Ten.

F. The abrasion weight reduction of dry-cast and underwater-cast and consolidated concretes should not exceed 2.5 and 4 percent, respectively.

G. The modulus of elasticity and thermal coefficient of expansion of the repair concrete should be compatible to those of the underlying base material.

11.11.3 Underwater Placement and Processing Techniques Stiff concrete can be cast under water using bottom-dumping buckets and skips or tilting pallets. A bottom-dumping bucket can be useful for casting discrete slugs of concrete for repairing small and scattered areas. The use of a skip can enable the placement of a uniformly thick and consolidated layer of concrete which can then be spread and compacted in place.

The placement device should be closed with water-resistant seals to reduce water erosion resulting from turbulent water that can occur while lowering the device in water. Special attention should be given to the configurations of the bottom gate to prevent

clogging or jamming of aggregate. The placement device should be filled level full and should have a large capacity to ensure continuous supply of fresh concrete and minimize the construction time. The bucket or skip should be lowered slowly in water, particularly when approaching the bottom, to avoid disturbing freshly-cast concrete. A quick-release bottom gate that can be operated manually or automatically should be provided to permit the discharge of concrete as a continuous mass. The drop distance of concrete in water should be minimized. Again, at the completion of casting, the retrieval of the placement device should proceed slowly near the slab surface to reduce disturbance of freshly-cast concrete.

Concrete may then be spread and compacted under water using heavy rollers which are moved gently back and forth over the fresh concrete. Positive measures should be taken to prevent the highly cohesive concrete from sticking to the roller. For example, the roller can be lined with a layer of Teflon or polyethylene. The compaction effort should be minimized by selecting proper roller sizes, concrete mixtures and lift thicknesses. Such parameters should be verified by underwater trial placements prior to actual repairs.

In casting and consolidating concrete under water, sufficient concrete should be provided to fill thin damaged areas and prevent rapid deterioration. The repair surface should be smooth and evenly aligned with the surrounding material. It is recommended to keep the length and thickness of the cast concrete lift small to reduce the needed compaction. For example, for a given roller size, it was demonstrated in Chapter Ten that less consolidation was required to spread and compact a slab measuring 18 in. in length than a 36 in. long slab. Similarly, fewer rolling passes were needed to consolidate a 4 in. lift than a 6 in. lift. The thickness of underwater-compacted concrete can be increased by casting and processing successive layers. Positive measures should be taken to avoid the formation of cold joints between these lifts. For example, the casting and consolidation of the top layer should be completed before the underlying concrete starts to stiffen, otherwise, the hardened surface must be properly prepared.

The compacting roller should be wide enough to cover the entire width of the spread concrete. The roller should be moved gently over the cast concrete until the desired slab thickness is obtained. The roller can be attached to guiding tracks which facilitate vertical and horizontal positioning. The roller and tracks can be mounted on a special work frame that can be bottom-supported by hydraulic jack leveling devices or can be supported from a jackup barge. Underwater operations can be manipulated by divers if the water is not excessively turbid. Otherwise remote control using special underwater sensors and TV cameras should be employed to guide the movements of the equipment.

Flat and sound repair surfaces can be obtained when properly designed stiff concrete is cast and compacted under water. For example, it was shown in Chapter Ten that a 4 in. concrete overlay can be formed by casting two 4 in. lifts of stiff concrete and compacting each three times with a concrete roller. The roller measured approximately 2 ft in diameter and provided a net 12.5 lb/in. passive pressure under water. The underwater-processed slab had an average relative density of 99 percent of control concrete which was cast and vibrated on land. The average in-place f'_c was approximately 10,000 psi, and the average bond strength with underlying hardened concrete was 280 psi.

11.12 Costs of Repair Concretes

Table 19 presents approximate unit costs of concrete-making materials that can be purchased in bulk quantities in Berkeley in 1989. The \$800/ton cost of powder silica fume consists of \$500/ton for the silica fume plus \$300/ton for freight. Slurry-added silica fume may cost approximately 60 percent more than powder silica fume.

Table 19 lists the proportions of three concretes suitable for repairing deep, relatively shallow and shallow scour holes. The cost of each employed material is calculated, then the total cost of all additives, including pozzolans, are given. The listed material cost of each concrete reflects the total cost of all individual materials. According to these estimates, the approximate costs of 1 yd^3 of concrete for repairing deep or

reinforced, relatively shallow and shallow scour holes may be $75, $79 and $143, respectively. While these prices are based on bulk material costs, the actual concrete cost may be higher. For example, concrete suppliers may charge an additional $10/yd^3 to $30/yd^3 for miscellaneous expenses, such as concrete delivery and waiting time.

Table 19. Typical Repair Concrete Costs

MIXTURE	UNIT COST, $	DEEP OR R/C K-FIELD	$	RELATIVELY SHALLOW MSFMPRO	$	SHALLOW-STIFF STIFF-PRO	$
CEMENT, #/CY	70/TON	600	21.0	600	21.0	745	26.1
SILICA FUME, #/CY	800/TON	42	16.8	42	16.8	112	44.8
FLY ASH, #/CY	50/TON	30	0.8	30	0.8	0	- -
WATER, #/CY	- -	276	- -	280	- -	274	- -
SAND, #/CY	15/TON	1320	9.9	1355	10.2	1305	9.8
PEA GRAVEL, #/CY	15/TON	1565	11.7	1610	12.1	1550	11.6
HRWRA, GAL/CY	5.5/GAL	2.1	11.6	1.8	9.9	2.4	13.2
KELCO AWA	5 / #	KELCO	- -	- -	- -	- -	- -
PROTEX AWA	3 / #	- -	- -	PROTEX	- -	PROTEX	- -
AWA,#/CY	- -	0.67	3.4	2.4	7.2	6.4	19.2
DE-AIR, #/CY	0.75/#	0	0.0	0.87	0.7	1.7	1.3
AEA, GAL/CY	2.25/GAL	0.09	0.2	0	0.0	0	0.0
CaCl2, #/CY	1 / #	0	0.0	0	0.0	17	17.0
ADMIXTURES, $			33		35		95
MATERIAL COST, $			75		79		143

Although stiff concrete is expensive, its use is limited to patching small areas and casting thin lifts. Concretes used to restore wear-damaged areas above water after dewatering the damaged area may also contain silica fume and HRWRA. Therefore, the cost of such concretes may not be significantly different from those developed for underwater repairs. However, the money saved by performing the repair under water without the need to build cofferdams for dewatering the repair area and without long interference wi h the operation of the hydraulic facility can be tremendous.

11.13 Planning for Repairs

Concrete suppliers, contractors and inspectors should be familiar with underwater repair operations and with the mixing and testing of concretes containing AWAs. All parties, including divers, should receive proper training to ensure successful repairs.

The effectiveness of debris removal and surface preparation systems should be verified prior to actual repair operations. Similarly, a pilot test should be carried out to cast the finalized concrete mixture under water using the select placement device. The shape and size of the underwater-cast slab should be similar to typical repair areas. The subsequent quality of the concrete should be examined to confirm the effectiveness of the repair system. Field-related problems should be identified and solved to increase the probability of success and cost effectiveness of actual repairs.

Special provisions should be specified when a fluid concrete is cast in flowing water. Water flow at the placement site should be reduced until the concrete starts to harden in order to minimize water erosion. The reduction of water velocity can be achieved by erecting temporary cofferdams for large repair areas or placing diversion boxes for small repair sites. Concrete may also be cast under special plates to protect the fresh concrete from moving water. Such plates should be designed to withstand currents and uplift pressures without adhering to freshly-cast concrete (Engineer Manual 1986).

Prior to underwater placements, all the aspects of the repair operations should be reviewed, such as mixing, handling and testing of the concrete, underwater casting procedures as well as locations of support equipments. Extra admixtures, additional placement pipes, pumps and air lifts should be available at the site. Contingency plans should be established to deal with foreseeable damaging factors, such as accidental discharge of concrete in water, blockages of the placement device, etc. Proper communication should be established between the divers and the key operators who remain above water.

11.14 Recommended Extensions for Future Research

Based on the findings of this study, it is felt that further work is needed to enhance the effectiveness of repair concretes and placement methods. Moreover, additional research should be undertaken to investigate concrete properties that may be affected by AWAs. Among the areas that require additional research are the following:

A. Refinement in admixture formulation, especially AWAs and compatible HRWRAs, to enhance their effectiveness and secure superior performance.

B. Further optimization in mix proportioning to reduce the required number and contents of additives and yield more economical repair materials.

C. The development of a reliable end plug (shut off valve) that can facilitate the termination of the placement and enable the closure of the pipe before moving it in water to repair neighboring scour holes.

D. The development of various systems and equipment that can be employed to spread and consolidate stiff concrete under water.

E. The placement of concrete under precast concrete or steel plates.

F. The determination of the influence of AWA type and concentration on strength development, modulus of elasticity and abrasion resistance of concretes of various fluidity and strength levels.

G. The investigation of the effect of AWAs on creep, drying shrinkage, chloride permeability and resistance to freeze-thaw exposure.

H. The suitability of underwater vacuum processing to enhance the durability of repaired surfaces. Excess water and surface air voids may be able to be removed by means of a vacuum to improve the in-place strength and wear resistance. This application may be suitable since the ambient hydrostatic pressure can increase the compaction of concrete and allow higher water extraction than normally possible on land.

Several of the optimized concretes, new test methods and underwater placement concepts developed in this research can be modified and extended to other uses in underwater as well as land-based applications. The following are possible applications that should be verified:

A. The use of AWAs in concretes, mortars and cement grouts normally employed in the construction and repair of submerged facilities, such as bridge piers, piles, offshore structures, etc. For example, the use of highly fluid concrete containing AWAs in conventional tremie operations can reduce mound formation at tremie locations and laitance at low areas, hence improving the productivity of subsequent construction.

B. The use of AWAs to replace silica fume in circumstances where silica fume would be employed to enhance the physical characteristics of fresh concrete, such as in shotcrete applications.

C. The incorporation of AWAs in cement grouts, such as those needed in post tensioning operations, to reduce bleeding and enhance bond development.

D. The addition of AWAs to concrete to stabilize entrained air bubbles in fresh concrete. This is important since the air volume often decreases with the duration of mixing and the increase in concrete temperature, thus resulting in unacceptable protection against freeze-thaw damage.

11.15 Closing Remarks

This study develops a new technology seeking to establish safe and economical applications of concrete under water. The research has shown that hydraulic structures can be repaired while they are still submerged under water. The developed concretes and construction procedures are believed to ensure economical and durable repairs which can reduce the rehabilitation requirements of hydraulic facilities and improve their safety and

integrity. Similarly, this new technology can be useful for applications other than repairs of wear-damaged surfaces, such as placements of massive tremie concrete, repair of submerged piles, construction of sloped surfaces under water, etc.

The investigation presented in this report is part of the Repair, Evaluation, Maintenance and Rehabilitation Research Program (REMR). It is an extension of a large research effort that was initiated at the Waterways Experiment Station, in Vicksburg, Mississippi. In addition to serving the U.S. Army Corps of Engineers, this report should benefit state agencies, regional authorities and private companies that are active in the field of construction, maintenance and repair of hydraulic, coastal and offshore facilities.

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Appendix A - Underwater Placement Methods

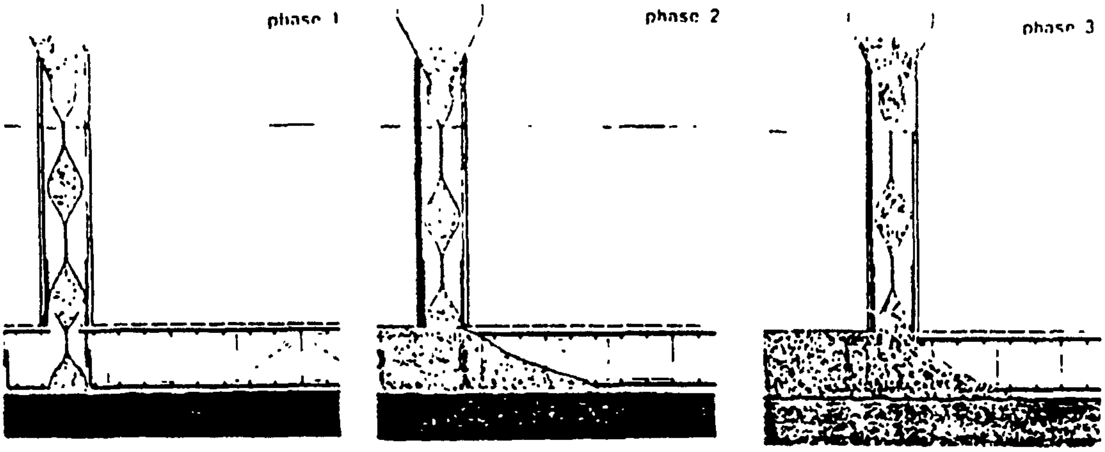


Fig. 1--Underwater Placement with a Hydro-valve Tremie Pipe

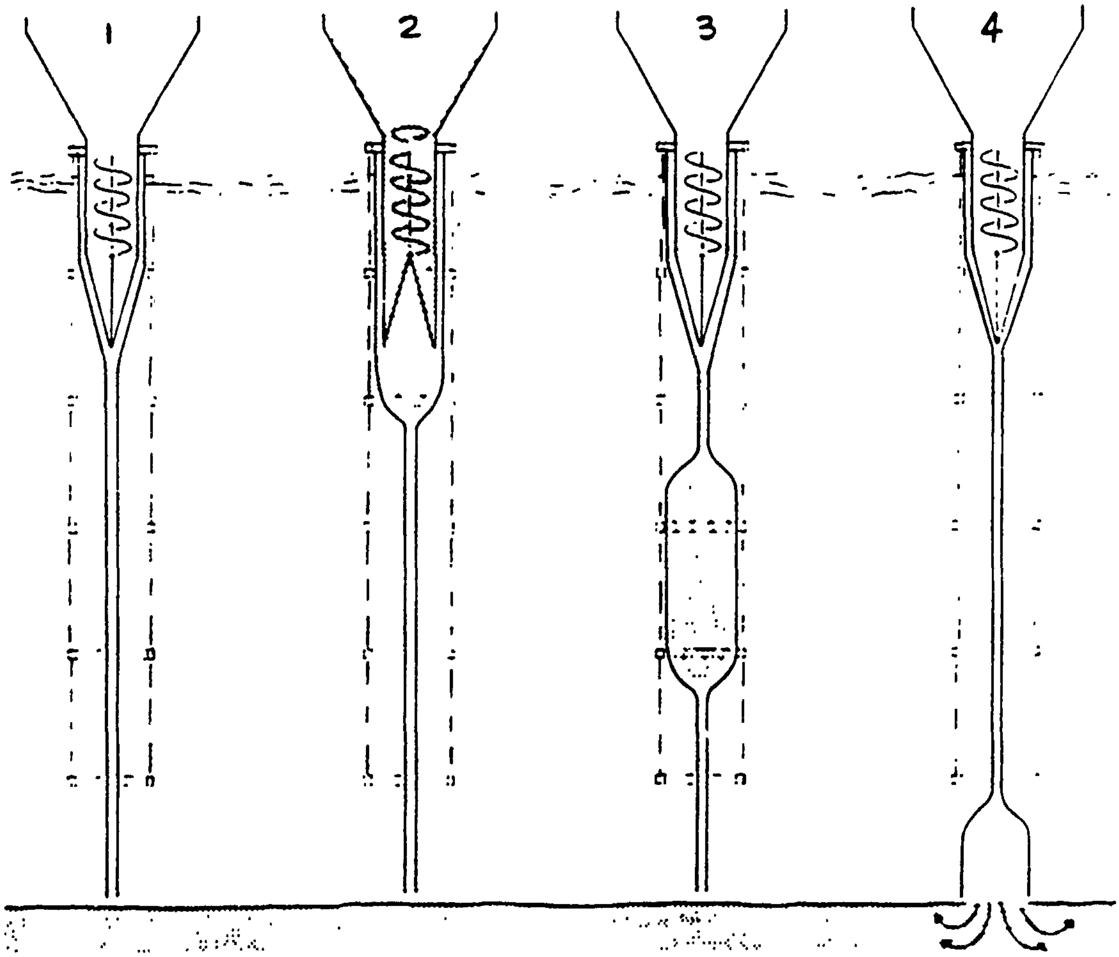


Fig. 2--Forced-feed Hydro-valve Tremie Pipe

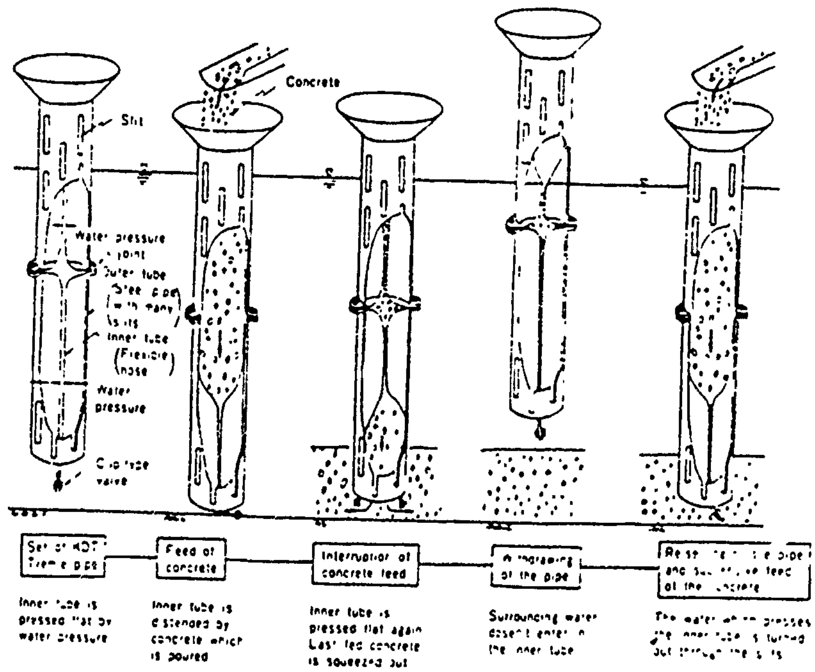
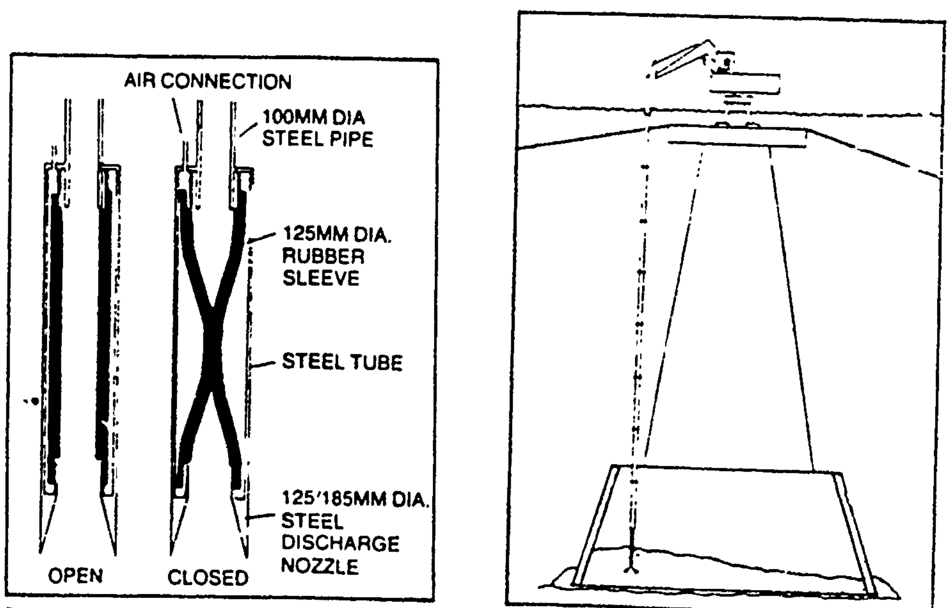


Fig. 3--Kajima's Double Tube Tremie Method



DISCHARGE VALVE FOR PUMPING BOOM

Fig. 4--Abetong-Sabema Pneumatic Valve

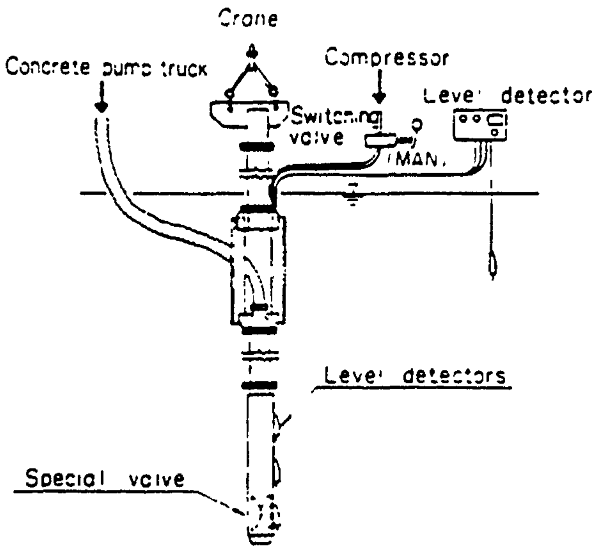


Fig. 5-- Shimizu NUCS Device

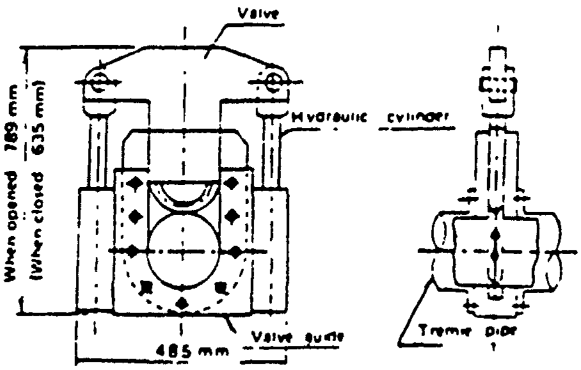


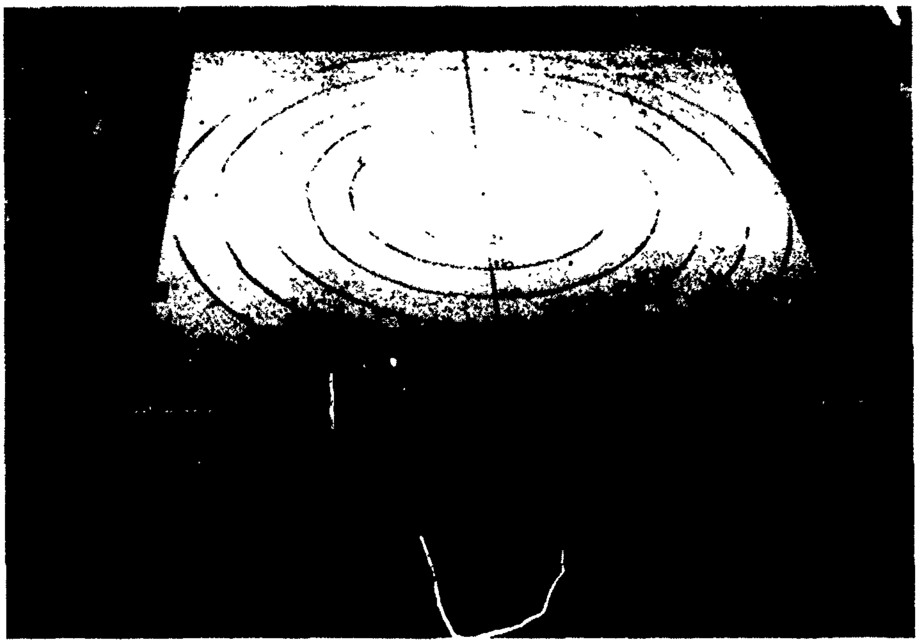
Fig. 6--KTS-1 Tremie Device and Crushing Valve

Appendix B - Procedures for Testing Concrete

Table 1. Kajima's Recommended Consistency levels for Various Placement Methods

Placement Method				Condition Of Structure	Consistency: Base Diameter Of Slump Cone (in.)	Consistency: DIN Flow Table (in.)
1				Slopped Surface	9 - 15	14 - 16
1	2	3		General Condition (Simple Shape Structure)	15 - 18	16 - 18
1	2	3	4	General Condition (Reinforced Concrete)	18 - 21	18 - 20
1	2	3	4	Filling Narrow Spaces	21 - 23	20 - 22
1	2	3	4	Filling Narrow, Deep Spaces	23 Or More	22 - 24

1 Bucket With Crane
2 Tremie Pipe
3 Pump Method -- Pipeline 150 ft Or Less
4 Pump Method -- Pipeline 150 ft To 600 ft



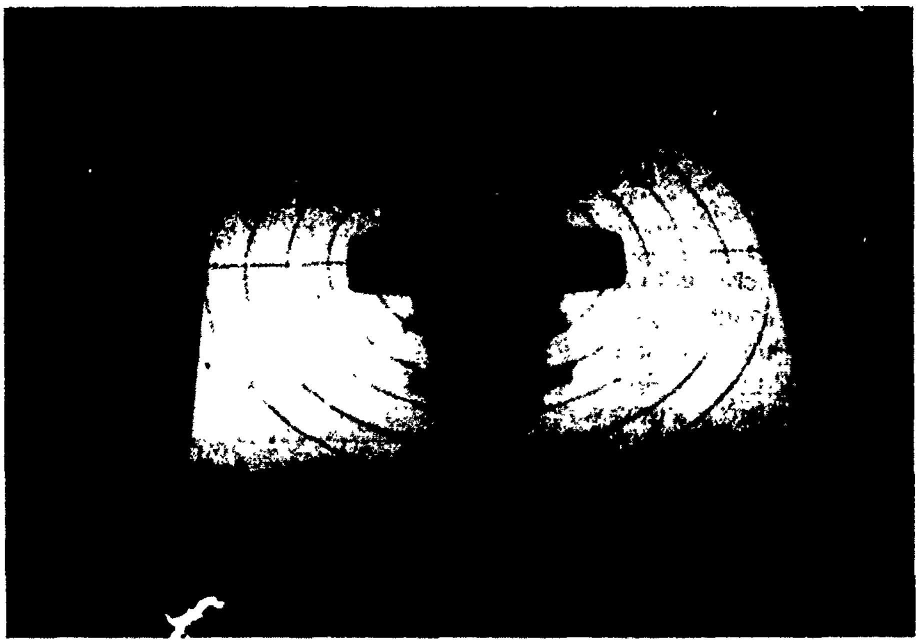
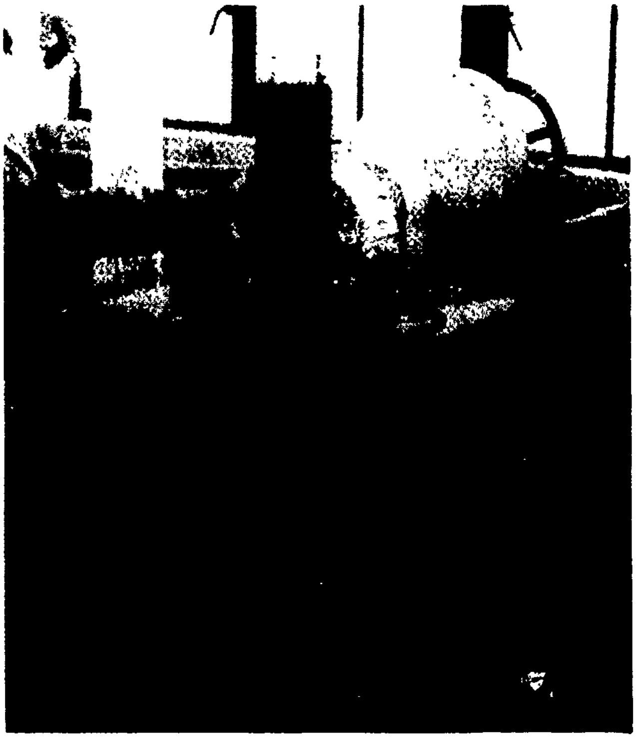


Fig. 7--Photographs of the DIN 1048 Flow Table



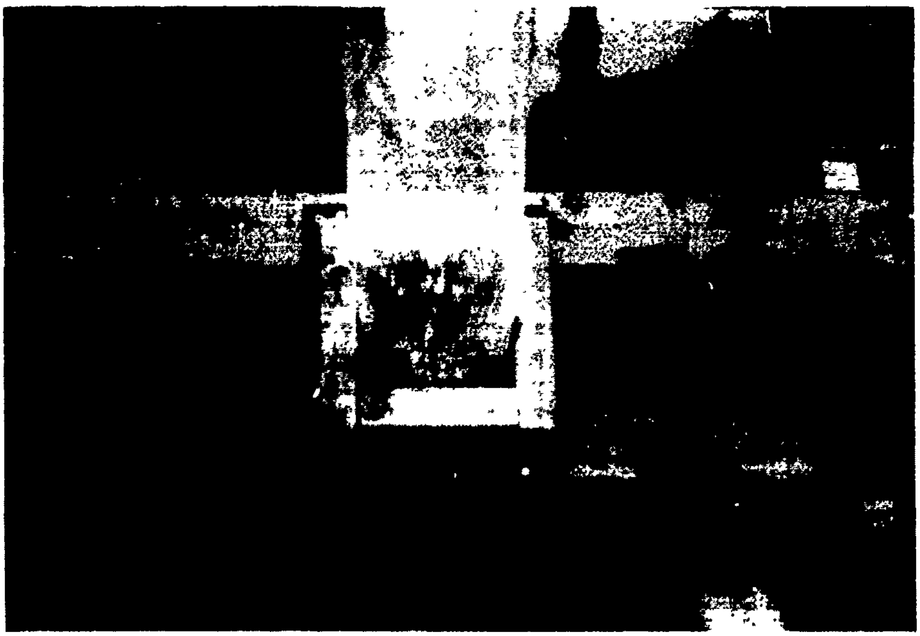


Fig. 8--Photographs of the Underwater Flow Test

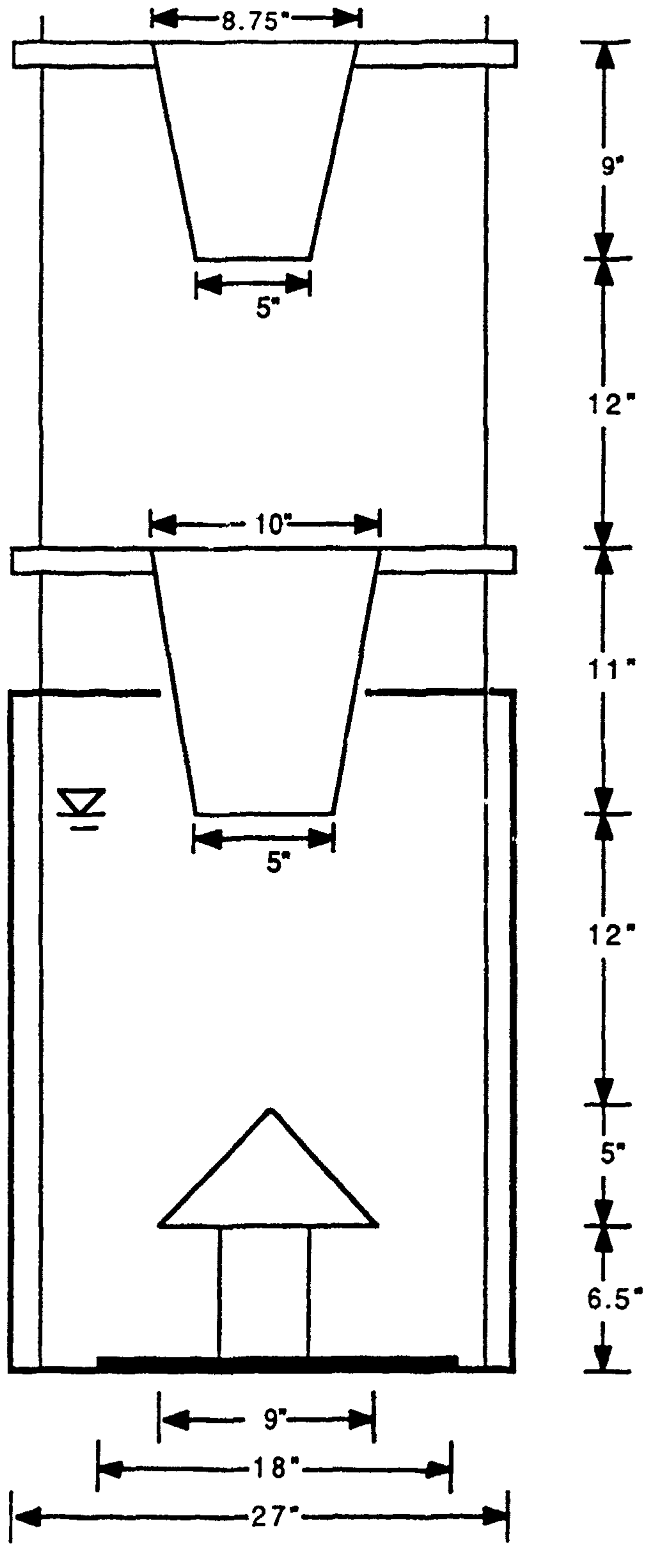


Fig. 9--Schematic of the Segregation Apparatus

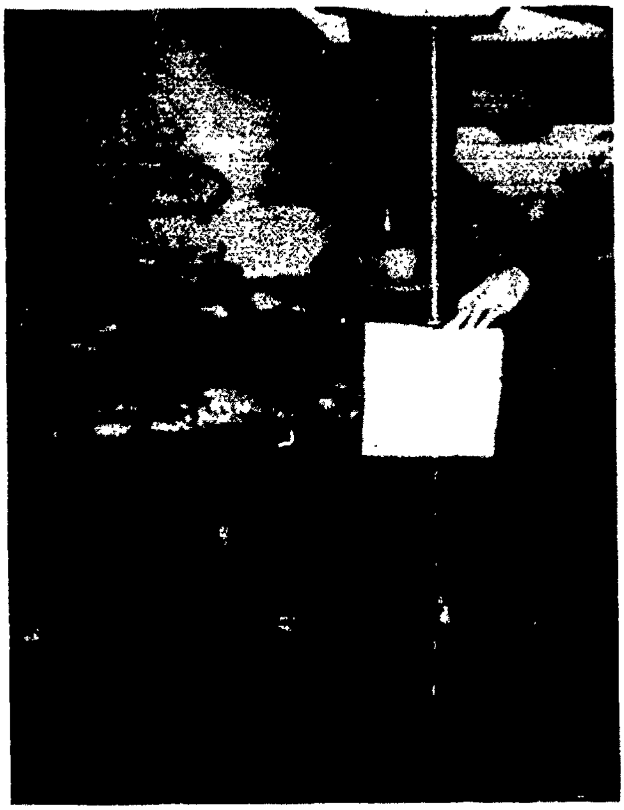


Fig. 10--Pictures of Segregation Tests of Dry-cast and Underwater-cast Concretes

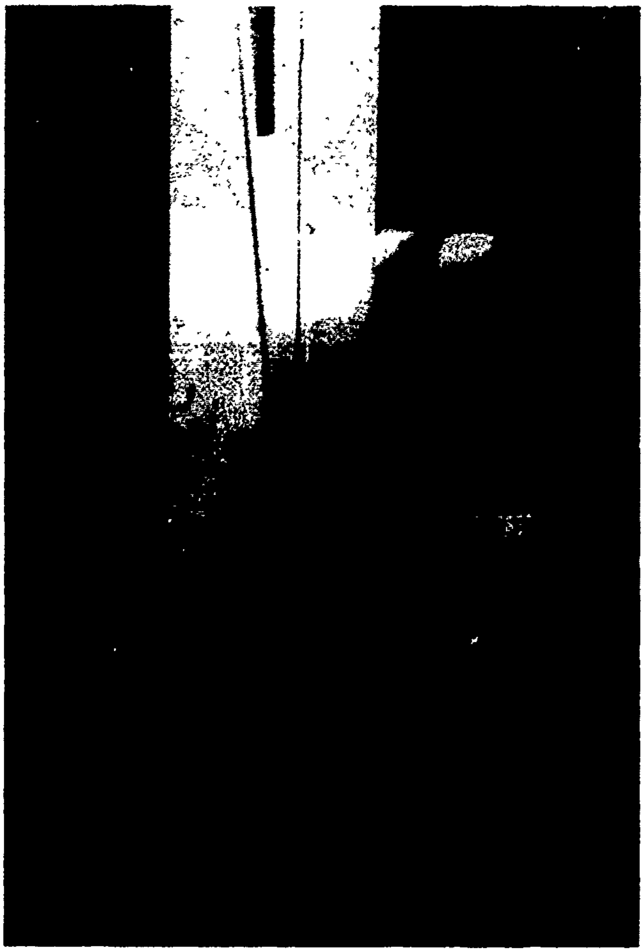


Fig. 11--Photograph of the Washout Test

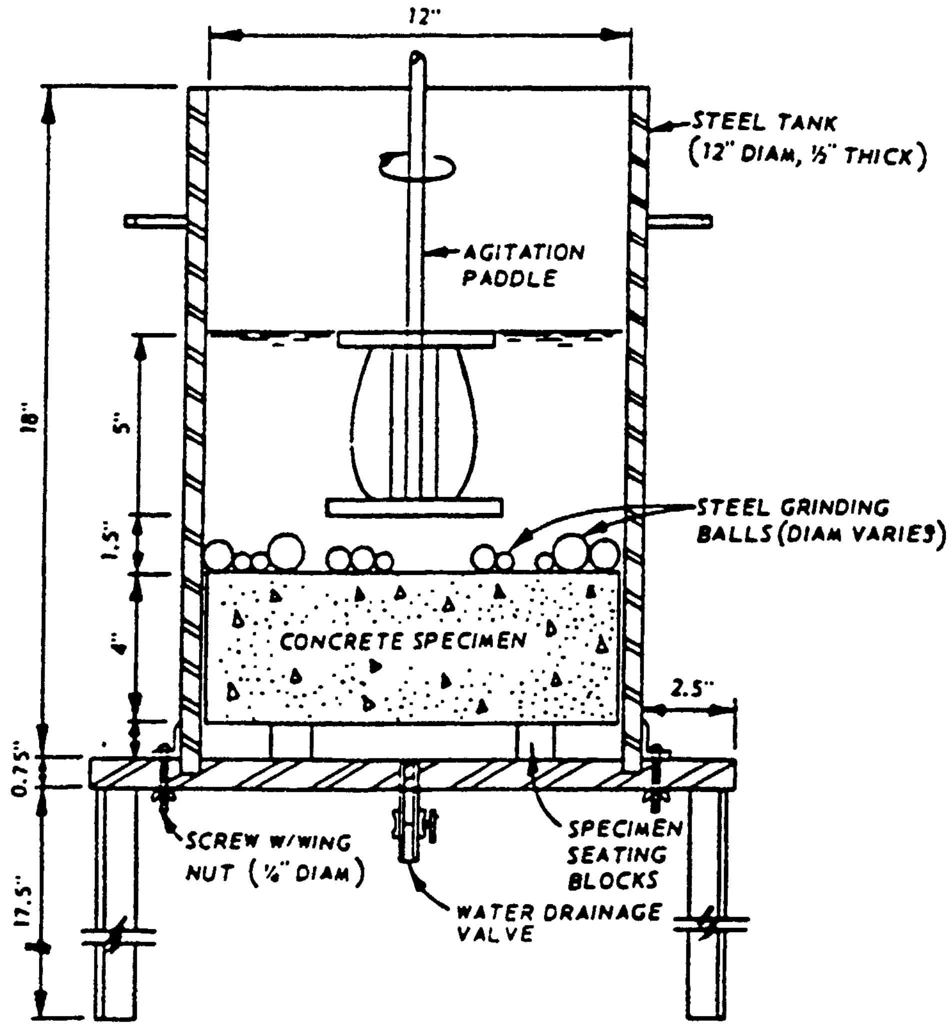
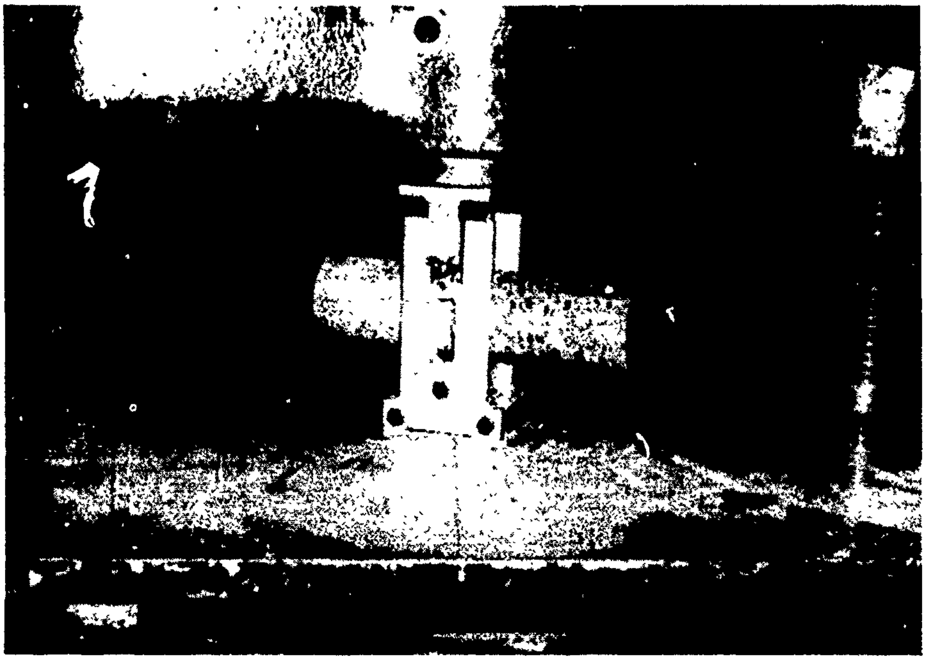


Fig. 12--Underwater Abrasion-erosion Testing Device

Fig. 13--Photographs of Casting Abrasion-erosion Specimens Under Water



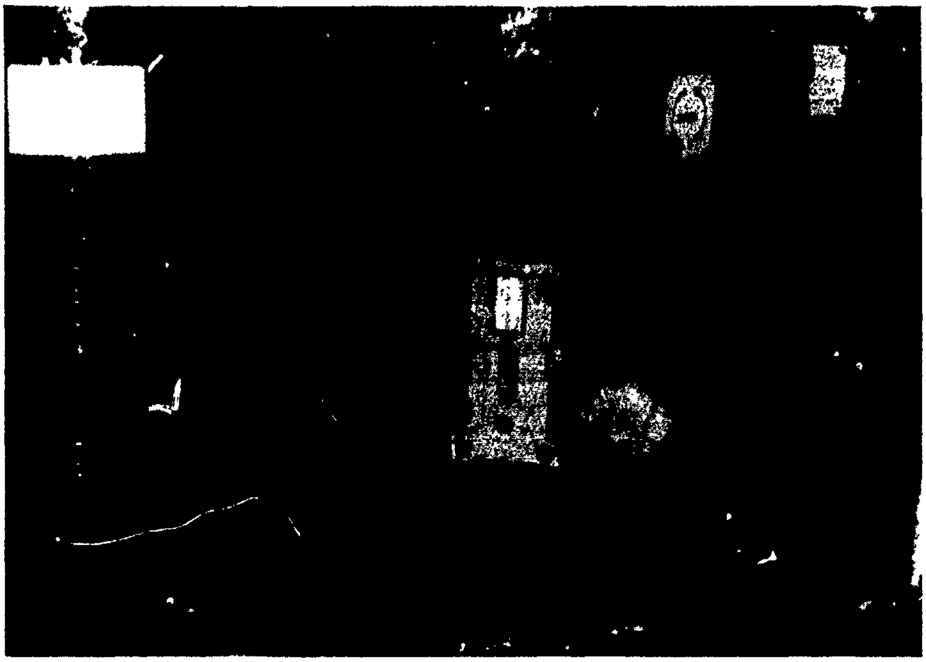


Fig. 14--Photographs of the Bond Test

Appendix C - Material Properties and Fluid Concrete Evaluation

Table 2. Portland Cement Chemical and Physical Properties

Chemical Analysis		Physical Properties		
Item	Percentage		Reported	Tested
SiO_2	22.03	Blaine, cm2/g	3346	
Fe_2O_3	3.67	Specific Gravity		3.15
Al_2O_3	4.03	Vicat: Final	2:19	
CaO	65.19	Initial	4:16	
MgO	0.88	Mortar F'c (psi)	w/c=.48	w/c=.45
SO_3	2.86	1 Day	1382	1700
Ignition Loss	0.98	3 Days	2623	2910
Insoluble Residue	0.16	7 Days	3711	4210
Na_2O	0.12	14 Days		5635
K_2O	0.2	28 Days	5936	
Total Alkali. as Na_2O	0.25			

Composition	Percentage
C3S	57.5
C2s	19.8
C3A	4.5
C4AF	11.2

Table 3. Properties of Mineral Additives

Chemical Composition	Silica Fume	Fly Ash
	Percentage By Weight	
SiO_2	92.5	67.9
Al_2O_3	0.5	16.2
Fe_2O_3	0.35	3.8
SO_3		0.4
CaO		4.3
C	2.2	
MgO	0.5	
K_2O	1	
Na_2O	0.6	
Physical Properties	**Silica Fume**	**Fly Ash**
Specific Gravity	2.39	2.3
Specific Surface, M2/g.	20	3.4

Table 4. Physical Properties of Aggregates

Aggregate	Fine	Coarse
Bulk Specific Gravity (S.S.D. Basis)	2.64	2.68
Absorption (%) (S.S.D. Basis)	1.45	1.34
L. A. Abrasion % Loss		
100 Revolution	3	
500 Revolution	14.4	

Table 5. Mineralogy of Pea Gravel

Rock Type	Percentage
Metagraywake	32 - 38
Graywacke	21 - 23
Chert	11 - 18
Metabasic Igneous	13 - 16
Vein Quartz	8 - 10
Granatic, meta volcanic, quartzite	1 - 5
Serpentine	1 - 2

Table 6. Properties of Concrete Additives

Admixture	Type	Form	Spec. Gravity	% Solids	Recommended Dosage
Protex T-2	AWA	P	1.3	All	0.5 - 1 % of CM Weight
Master Builders PT-802	AWA	P	1.35	All	1 - 1.5 % of CM Weight
Rescon-T	AWA	P	- -	All	9 - 18 lb/cyd
Kelco Whelan Gum (K1A96)	AWA	P	- -	All	0.05 - 0.4 % CM Weight
Hitech Z10-A	AWA	P	- -	All	3 % of CM Weight
Halliburton D-Air 1	De-air	P	1.35	All	0.1- 0.25 % of CM Weight
Sikament FF86	HRWRA	A	1.21	40	10 - 24 fl oz/100# CM
Sikament FF	HRWRA	A	1.23	40	10 - 24 fl oz/100# CM
Melment	HRWRA	A	1.11	- -	20 - 40 fl oz/100# CM
Plastiment	WRA	A	1.19	25	2 - 4 fl oz/100# CM
Plastocrete 169	WRA	A	1.21	40	4 - 6 fl oz/100# CM
Sika AER	AEA	A	1.05	17.2	0.5 - 1.5 fl oz/100# CM
Grace Daravair	AEA	A	1.2	- -	0.75 - 3 fl oz/100# CM

A = Aqueous P = Powder

Table 7. Summary of Tests Performed

Test	Standard	Comments
Slump - Static Test	ASTM C 143	Tested at 65 and 85 Degree F
Slump Loss		Monitored for 120 min.
Flow Table - Dynamic Test	DIN 1048	Tested at 65 and 85 Degree F
Flow Table Loss		Monitored for 120 min.
Unit Weight	ASTM C 138	
Air Content	ASTM C 173	
Bleeding	ASTM C 232	
Segregation	None	Cast Above and Under Water
Washout Weight Loss	None	Monitored for120 min.
Under Water Flow	None	
Time of Setting	ASTM C 403	2 Specimens per Test
Compressive Strength	ASTM C 39	3 Cylinders 4 x 8 in.
Splitting Tensile Strength	ASTM C 496	3 Cylinders 4 x 8 in.
Modulus of Rupture	ASTM C 78	2 Beams 3 x 3 x 20 in.
Abrasion Resistance	CRD C 63	2 Disks Cast in the Dry 2 disks Cast Under Water
Bond Strength with Steel	ASTM C 234	4 Molds Cast in the Dry 4 Molds Cast Under Water
Temperature Development	None	

Table 8. Trial Mix Proportions and Properties

TRIAL MIXTURES	1	2	3	4	5	6	7	8
CEMENT, PCY	598	632	581	571	566	580	590	577
SILICA FUME, % CEM.	15	10	13	14	11	11	9	11
FLY ASH, % CEM.	0	0	0	0	3	0	0	5
TOTAL CM, PCY	688	695	656	651	645	644	644	670
W/CM	**0.44**	**0.46**	**0.4**	**0.45**	**0.42**	**0.43**	**0.42**	**0.4**
SAND % OF AGG. VOL.	42	42	45	47	46	46	46	44
HRWRA	--->	MELMENT	<---	--->	--->	SIKA FF	<---	<-- NEW
FL. OZ./100# CM	20	54	38.5	26	26	28	27	30
WRA	--->	--->	--->	PLASTIMENT		<---	<---	<---
FL. OZ./100# CM	16.5	18	8.5	7	7	7	6	7
AEA	GRACE		--->	--->	GRACE	<---		GRACE
FL. OZ./100# CM	2		0.9	0.5	1	0.9		0.6
AWA		PROTEX					PROTEX	
% OF CM		0.15					0.15	
DE-AIR, % OF CM		0.08					0.1	
UNIT WT., PCF	135	143.3	146.5	150	147.5	146.5	146.6	150
AIR VOL., %	10.5	6	5.5	2.5	4.75	5.5	4.4	2.75
MIX + ADJUST, MIN.	30	25	20	25	30	20	30	30
SLUMP, IN. INITIAL	6	7	7.25	8	9	8	8.5	9.5
+ 30 MIN.	5.75	7	6.5	6.75	8.25	8	7	8.5
+ 60 MIN.		7	4.5	6.5	6	6.5	4	
+ 90 MIN.				4.5	4.75	4.5	3	
COMMENTS				WET	NICE	<---	<---	V. WET
				BLEEDS	FLOWS	<---	<---	REPEAT
					WELL	<---	<---	
					EVEN AT	<---	<---	
					90 MIN.	<---	<---	
3 X 6 IN. F'c, PSI			7390	6910	6750	7205	7045	
AGE, DAYS			14	14	14	14	14	
3 X 6 IN. F'c, PSI						8310		
AGE, DAYS						28		
FINAL SETTING, HRS.	120	120	30	25	30	31	27	

Table 8. (Continued)

TRIAL MIXTURES	9	10	11	12	12B	12C
CEMENT, PCY	574	572	588	572	575	571
SILICA FUME, % CEM.	11	11	11+	13	13	13
FLY ASH, % CEM.	5	5	5	5	5	5
TOTAL CM, PCY	666	664	682	675	679	674
W/CM	**0.37**	**0.4**	**0.36**	**0.34+**	**0.35**	**0.35**
SAND % OF AGG. VOL.	45	45	45+	46	46	46
HRWRA	NEW SIKA FF		--->	SIKAFF86		<---
FL. OZ./100# CM	29	31	27	24	23	23
WRA	--->	PLASTIMENT		<---	SIKA169	PLASTI.
FL. OZ./100# CM	7	7.5	7	5	6	5
AEA	--->	GRACE	<---	<---	SIKA	<---
FL. OZ./100# CM	0.6	0.75	0.75	1	0.75	0.75
AWA						
% OF CM						
DE-AIR, % OF CM						
UNIT WT., PCF	148.47	148.61	151.5	148.87	149.8	149
AIR VOL., %	3.75	4	3	4.15	4.1	4
MIX + ADJUST, MIN.		25	20	20	15	25
SLUMP, IN. INITIAL	8	8.5	9.5	8	9	8
+ 30 MIN.	3.5	8		7.75	3.5	5.5
+ 60 MIN.		7.5		7.25		
+ 90 MIN.		5				
FLOW, IN. INITIAL						18
+30 MIN.						15.5
COMMENTS	REPEAT	A BIT	TOO WET	STICKY	STICKY	STICKY
		STICKY	REPEAT	NICE	<---	
		FLOWS	ADD	FLOWS	BIT WET	
		BIT TOO	SAND	ADD	SLUMP	
		FLUID	SF	WATER	LOSS	
3 X 6 IN. F'c, PSI		4775	5545	6180	6325	6460
AGE, DAYS		7	7	7	7	7
3 X 6 IN. F'c, PSI		7715	5545	9160	8140	8890
AGE, DAYS		28	28	28	28	28
FINAL SETTING, HRS.		40	72	23	< 15	19

Table 8. (Continued)

TRIAL MIXTURES	13	13B	13C	14	14B	15	16
CEMENT, PCY	569	592	595	611	623	599	510
SILICA FUME, % CEM.	10	10	10	4	4	7	6 +
FLY ASH, % CEM.	5	5	5	5	5	5	25
TOTAL CM, PCY	654	681	684	666	679	671	668
W/CM	**0.36+**	**0.37**	**0.37**	**0.43+**	**0.45**	**0.41**	**0.41**
SAND % OF AGG. VOL.	46	46	46	46	46	46	46
HRWRA	--->	--->	--->	SIKAFF86	<---	<---	<---
FL. OZ./100# CM	26	25	24+	31	30	31	33.2
WRA	--->	--->	PLASTIMENT		<---	<---	<---
FL. OZ./100# CM	5		4+	5		5 -	
AEA							
FL. OZ./100# CM							
AWA	--->	--->	--->	PROTEX	<---	<---	<---
% OF CM	0.15	0.15	0.15	0.5	0.5	0.35	0.35
DE-AIR, % OF CM	0.1	0.11-	0.11-	0.14+	0.15+	0.12	0.13-
UNIT WT., PCF	149.54	149.4	149.94	146.21	146.75	147.14	145.2
AIR VOL., %	4.25	3.5	3.25	4.25	4.5	4	3.25
MIX + ADJUST, MIN.	20	15	15	15	15	15	20
SLUMP, IN. INITIAL	8.5	8.5	9.5	9.25	9.75	9.75	10.5
+ 30 MIN.	7.75	4.75	8.75	9	9.75	9.75	10.25
+ 60 MIN.	8.25	3	8.25	9	9.75	9.25	
+ 90 MIN.	7		7	8.75	9.5	9	
FLOW, IN. INITIAL			18.5				22.5
+30 MIN.			17				20.5
+ 60 MIN.			---				20
+ 90 MIN.			16.5				
WASH OUT # 1							2.49
# 2							4.22
# 3							5.82
COMMENTS	STICKY	STICKY	STICKY	STICKY	STICKY	STICKY	BLEEDS
	NICE	NICE	NICE	NICE	V. NICE	<---	V. NICE
	FLOWS	FLOWS	FLOWS	FLOWS	FLOWS	FLOWS	FLOWS
	ADD		ADD	<---	WELL	WELL	V. WELL
	WATER		PLAST5	WATER	COHESIVE	<---	COHESI.
3 X 6 IN. F'c, PSI	5390		5660	3995	4540	4325	3650
AGE, DAYS	7		7	7	7	7	7
3 X 6 IN. F'c, PSI	9130			6270	6255	8010	
AGE, DAYS	28	28	28	28	28	28	28
FINAL SETTING, HRS.	30+	< 15	18	85+	< 18	85+	15

Table 8. (Continued)

TRIAL MIXTURES	17	SLAG	17B	17C	17D	18	18B	18C	18D
CEMENT, PCY	376	373	376	375	378	604	595	601	579
SILICA FUME, % CEM.	11+	12	12	12	12	7	7	7	7
FLY ASH, % CEM.	0	0	0	0	0	5	5	5	5
SLAG, % 0F CEM.	66.7	66.7	66.7	66.7	66.7	0	0	0	0
TOTAL CM, PCY	669	666	669	670	675	676.5	666	673	649
W/CM	**0.42**	**0.43**	**0.42**	**0.44**	**0.43**	**0.4**	**0.42**	**0.43**	**0.43**
SAND % OF AGG. VOL.	46	46	46	46	46	46	46	46	46
HRWRA	--->	--->	--->	--->	SIKAFF86	<---	<---	<---	<---
FL. OZ./100# CM	34	36	32	37.8	38	33	36	38	38
ACCELERATOR			**FL**	**161CACL2**				**FL**	**161CACL2**
CONCENTRATION			32 OZ/	**2H20**				20 OZ/	**2H2O**
			100#	2%				100#	2%
			C.M.	C.M.	0.75			C.M.	C.M.
AWA	--->	--->	PROTEX	<---	<---	MASTER BUILDERS			<---
% OF CM	**0.35**	**0.35**	**0.35**	**0.35**	**0.35**	0.35+	0.70+	0.85	0.85
DE-AIR, % OF CM	0.13-	0.15	0.17	0.15-	0.17	0.13	0.15-	0.13	0.11
UNIT WT., PCF	145.8	143.1	143.8	144.2	144.8	147	146.2	146.2	141.2
AIR VOL., %	3.25	4.75	3.8	3.25	3.5	3.75	3.25	2.75	6
MIX + ADJUST, MIN.	20	10	10	10	10	15	20	10	10
SLUMP, IN. INITIAL	10.25	10.25	10.35	10.5		10	9.75	10.25	10
+ 30 MIN.	10	10.5	- -	10.25		8.75	8.75	9.85	9.75
+ 60 MIN.		10.5	8.75	- -		STIFFER		- -	9.35
+ 90 MIN.		9.5	8.4	9.75				9	9
FLOW, IN. INITIAL	20.75	20.75	20.5	20.75	21.75	23.75	21.5	21.5	21.5
+30 MIN.	19.25	22.5	18.75	20.75		22.5	20.5	20.5	21
+ 60 MIN.	17.5	21.25	18.25	- -				19.25	20.5
+ 90 MIN.		20	18	20				18.75	19.75
WASH OUT # 1	1.84					4.71	2.58		
# 2	3.09					7.2	3.86		
# 3	4.18					9.42	5.15		
COMMENTS	BLEEDS					<---	GOOD	<---	V.GOOD
	NICE		NICE	<---	<---	TOO	V. NICE	<---	<---
	FLOWS	<---	<---	<---	<---	FLUID	FLOWS	<---	<---
	WELL	<---	<---	<---	<---		V. WELL	<---	<---
	COHESI.	<---	<---	<---	<---	OK	OK	OK	OK
3 X 6 IN. F'c, PSI	4670	3780							
AGE, DAYS	7	7							
FINAL SETTING, HRS.	< 15	72/75	37/40	68	9	< 20	20	34/36	34/36

Table 8. (Continued)

TRIAL MIXTURES	18E	19	19B	20	MSFMP	21	22
CEMENT, PCY	590	634	622	589	595	595	600
SILICA FUME, % CEM.	7	4	4	10	7	7	7
FLY ASH, % CEM.	5	5	5	5	5	5	5
SLAG, % OF CEM.	0	0	0	0	0	0	0
TOTAL CM, PCY	660	691	678	678	666	666	672
W/CM	**0.44**	**0.41**	**0.45**	**0.37+**	**0.42**	**0.43**	**0.42**
SAND % OF AGG. VOL.	46	46	46	46	46	46	46
HRWRA	--->	--->	--->	SIKAFF86	<---	<---	<---
FL. OZ./100# CM	38	30	33	26+	34	38	38
ADDITIVE	**CACL2**			PLAST.			
CONCENTRATION	**ANHYD.**			4.5+OZ/			
	1.5%CM			100#CM			
AWA	--->	MASTER BUILDERS		<---	--->	PROTEX	<---
% OF CM	**0.85**	**.50+**	**1.35**	**0.40 +**	**0.35**	**0.35**	**0.35**
DE-AIR, % OF CM	0.12+	0.17-	0.18-	0.13-	0.12	0.13+	0.12
UNIT WT., PCF	143	147	146.2	148	145.9	145.7	146.3
AIR VOL., %	5.5	3.25	2	3.25	4	4.25	4
MIX + ADJUST, MIN.	15	15	20	20	10	20	30
SLUMP, IN. INITIAL	10	10.5	9.75	9	9.75	9.75	9.75
+ 30 MIN.	10.25	8.75	8.5	7.25	10	9.5	9.25
+ 60 MIN.	8.25	STIFFER		<---	9.6	8.5	9
+ 90 MIN.	7.5				8.75	8	8.5
FLOW, IN. INITIAL	21.5	24	19.75	19	20.5	20	20.25
+30 MIN.	20	23	18.5	17.75	20.25	19.75	19.5
+ 60 MIN.	17.75				19.25	18.5	18.25
+ 90 MIN.	17.25				17.5	17.75	17.25
WASH OUT # 1	1	4.07	0.89	2.05	1.06	1.48	1.35
# 2	2.1	6.15	2.32	3.08	2.04	2.92	2.5
# 3	2.85	8.54	3.22	4	2.94	3.7	3.25
COMMENTS	V. NICE	<--- +	V. NICE	NICE	NICE	<---	V.NICE
	FLOWS	TOO	FLOWS	FLOWS	<---	V. NICE	F=18.5
	WELL	FLUID	WELL	WELL	<---	<---	W/34,
	COHES.				COHESV	<---	F=19.75
	OK	OK	COHESL	<---			W/37
3 X 6 IN. F'c, PSI					5740		
AGE, DAYS					7		
3 X 6 IN. F'c, PSI					7985		
AGE, DAYS					28		
FINAL SETTING, HRS.	23/25	< 20	LONG	<---	14.5		

Table 8. (Continued)

TRIAL MIXTURES	27	27A	27B	28	28A	28B	28C	28D	28E
CEMENT, PCY	595	595	595	622	607	607	624	594	593
SILICA FUME, % CEM.	7	7	7	7	7	7	7	13	13
FLY ASH, % CEM.	5	5	5	5	5	5	5	5	5
SLAG, % 0F CEM.	0	0	0	0	0	0	0	0	0
TOTAL CM, PCY	666	666	666	697	680	680	699	701	700
W/CM	**0.44**	**0.44**	**0.45**	**0.37**	**0.39**	**0.38**	**0.3**	**0.36**	**0.37**
SAND % OF AGG. VOL	46	46	46	46	46	46	46	46	46
HRWRA	--->	--->	--->	SIKAFF86		<---	<---	<---	<---
FL. OZ./100# CM	36	40	40	34	40	39	32	27	34
WRA						--->		PLASTIMENT	
FL. OZ./100# CM						5.5	5	5.5	6.5-
AEA						--->	--->	SIKA	<---
FL. OZ./100# CM						1	0.9	1	1
CACL2, % OF CM	0.75	0.5	0.75	0	0.75	0	0	0	0.5
AWA	RESCON	<---	<---	--->	Z10/A	<---	Z10/A	Z10/A	Z10/A
% OF CM	3.5	2.5	3	3	3.5	4.8	4.8+	5+	7
DE-AIR, % OF CM	0.12	0.06	0.09	0	0	0	0	0	0
UNIT WT., PCF	146.2	146.7	146	151.3	151.5	145	149	146.6	145.8
AIR VOL., %	2.25	2.25	2.5	1	1.5	3.75	3.25	3.5	4.25
MIX + ADJUST. MIN.	20	15	10	20	15	15	15	15	15
SLUMP, IN. INITIAL	9.5	10	9.75	TOO	4.25	TOO	8.75	8	7.5
+ 30 MIN.	9.25			MUCH	2	MUCH	2.75		5
+ 60 MIN.									
+ 90 MIN.									
FLOW, IN. INITIAL	18.75	20.5	19		20.5		25	20.5	22.75
+30 MIN.	17.5				18.5		17.75	18.5	20.25
WASH OUT # 1	0.2	0.93			1.52		2.21	1.17	1.35
# 2	0.8	1.96			3.29		3.83	2.69	2.9
# 3	1.33	2.75			4.67		5.31	4	4.4
COMMENTS	COHES.	COHES.	COHES.	TOO	FLUID	TOO	VERY	MED.	OK
	A BIT	FLOWS	DO NOT	FLUID	ONLY	FLUID	FLUID	COHES.	DOES
	STIFF	WELL	USE	BLEEDS	WHEN	Z10/A	STIFF	FLUID	NOT
			DE-AIR		VIBRATEI	NO	FAST	WHEN	FLOW
						GOOD		SHAKED	WELL
FINAL SETTING, HRS.		18		< 20			48	< 46	45

Table 8. (Continued)

TRIAL MIXTURES	29	29A	29B	29C	29D	29E	29F	29G
CEMENT, PCY	608	607	605	593	605	605	600	603
SILICA FUME, % CEM.	7	7	5	5	5	5	7	7
FLY ASH, % CEM.	5	5	5	5	5	5	5	5
TOTAL CM, PCY	681	680	666	652	665	666	672	675
W/CM	0.43	0.46	0.48	0.45	0.45	0.47	0.46	0.46
SAND % OF AGG. VOL.	46	46	46	46	46	46	46	46
HRWRA	--->	--->	--->	SIKAFF86	<---	<---	<---	<---
FL. OZ./100# CM	50	44	51	45	48	47	44	50
WRA				PLASTIMENT		<---		
FL. OZ./100# CM				5.5	4	3		
AEA	--->	--->	--->	SIKA		<---	<---	<---
FL. OZ./100# CM		0.75	1.25	1.5	1	0.75	1.25	1.75
AWA	--->	--->	--->	KELCO	<---	<---	<---	<---
% OF CM	0.18	0.28	0.29	0.26	0.28	0.28	0.28	0.08
CACL2, % OF CM						0.75		
UNIT WT., PCF	148.9	147.7	145.4	141.4	144.5		144.3	145
AIR VOL., %	1.5	2	3	5.75	4.75		3.75	3.25
MIX + ADJUST, MIN.	15	15	15	15	15	15	15	15
SLUMP, IN. INITIAL			9.5	10	9.5	9	9.5	11.25
+ 30 MIN.			8.5	9.75	9.5	7.5	9.25	
+ 60 MIN.			7.5	9.25	8.5	7.25	8.5	
+ 90 MIN.				9	8.25		7.5	
FLOW, IN. INITIAL	21	19.5	19.75	20.5	19.5	19.5	19.5	27
+30 MIN.	19.75	18.5	18	20.5	18.5	18	18.5	
+ 60 MIN.			16.75	18.5	17.75	17.5	17.75	
+ 90 MIN.			0	17	17		16.5	
WASH OUT # 1	1.9	0.73	0.13	0.67	0.59	0.09	0.4	4
# 2	3.72	1.72	1.03	2.04	1.48	1.71	1.08	7.1
# 3	4.93	2.24	1.53	2.8	2.34	2.82	1.79	10.2
3 X 6 IN. F'c, PSI			7585	7295	7840		6850	6900
AGE, DAYS			56	56	56		28	28
FINAL SETTING, HRS.	14	9.5/11	20/22	42/44	38/40	43/47	14/16	

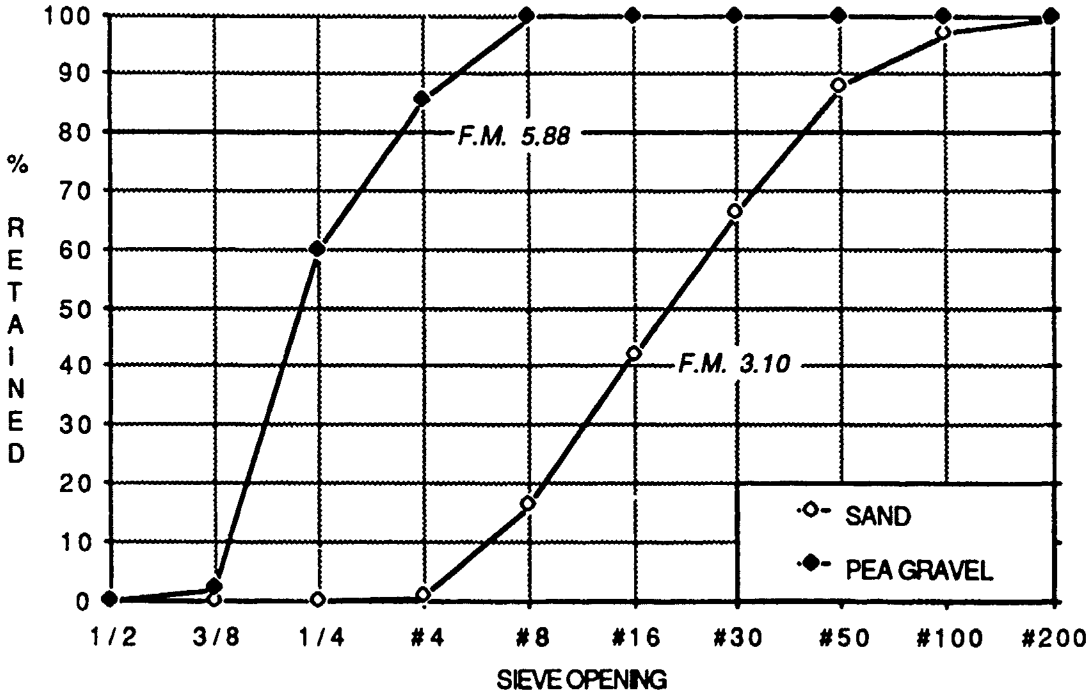
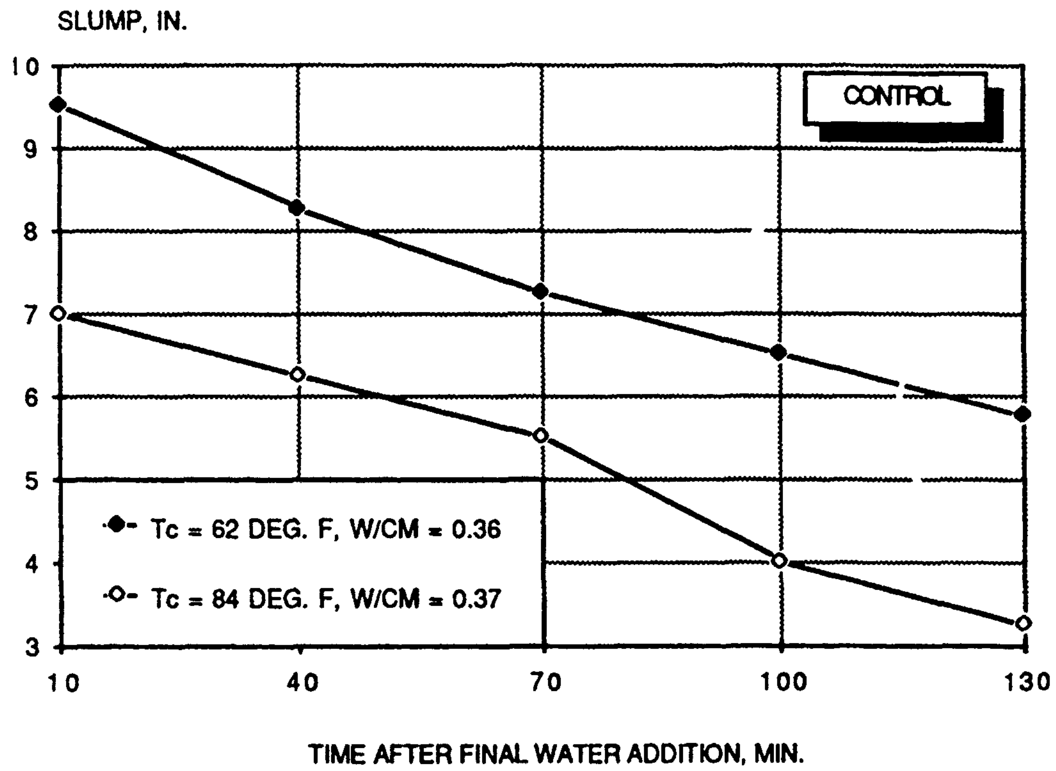


Fig. 15--Aggregate Gradation



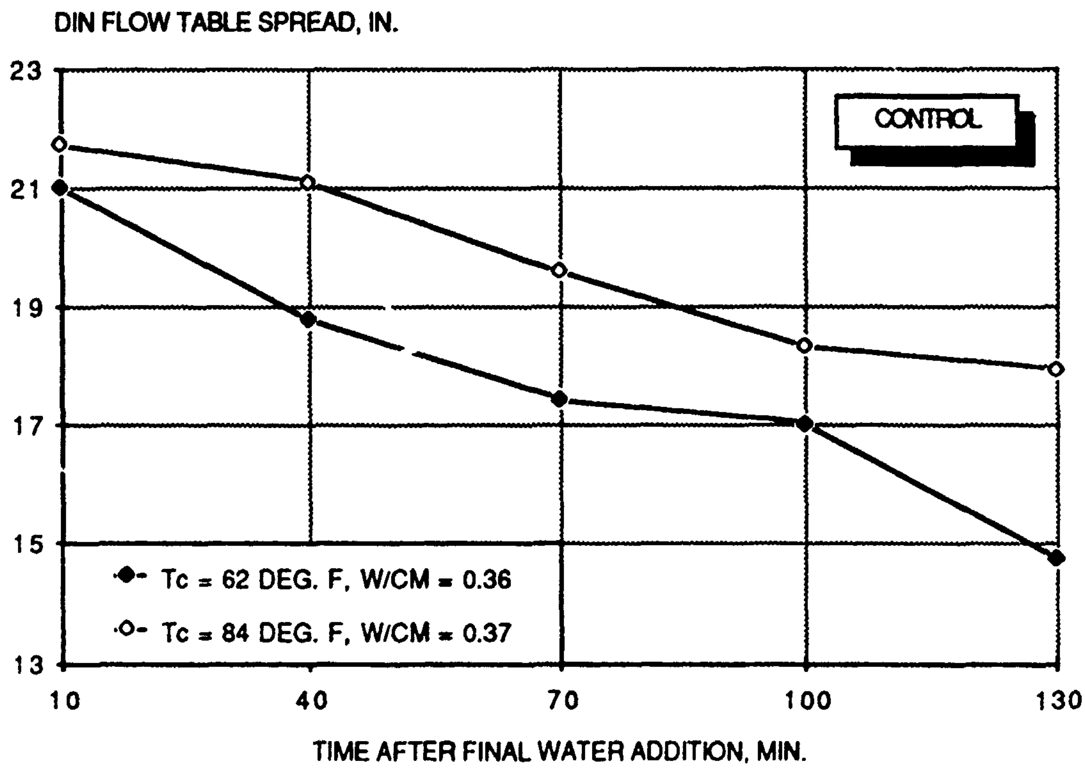
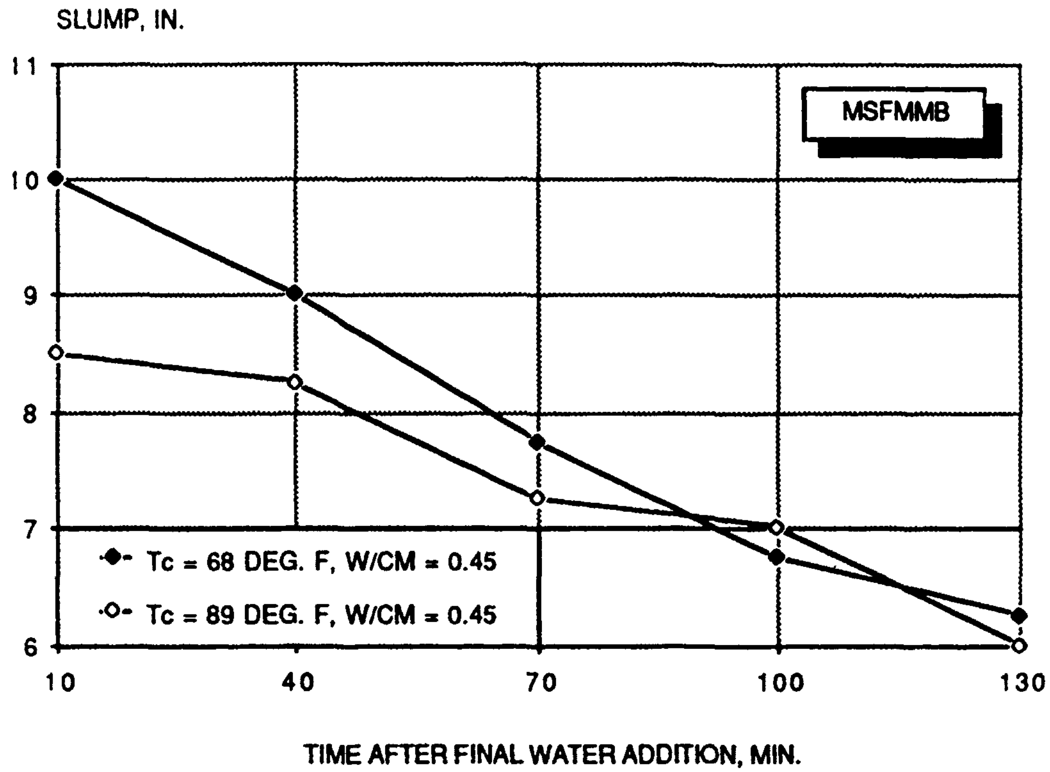


Fig. 16, 17--Slump and Flow Retentions of CONTROL Mix at Various Temperatures



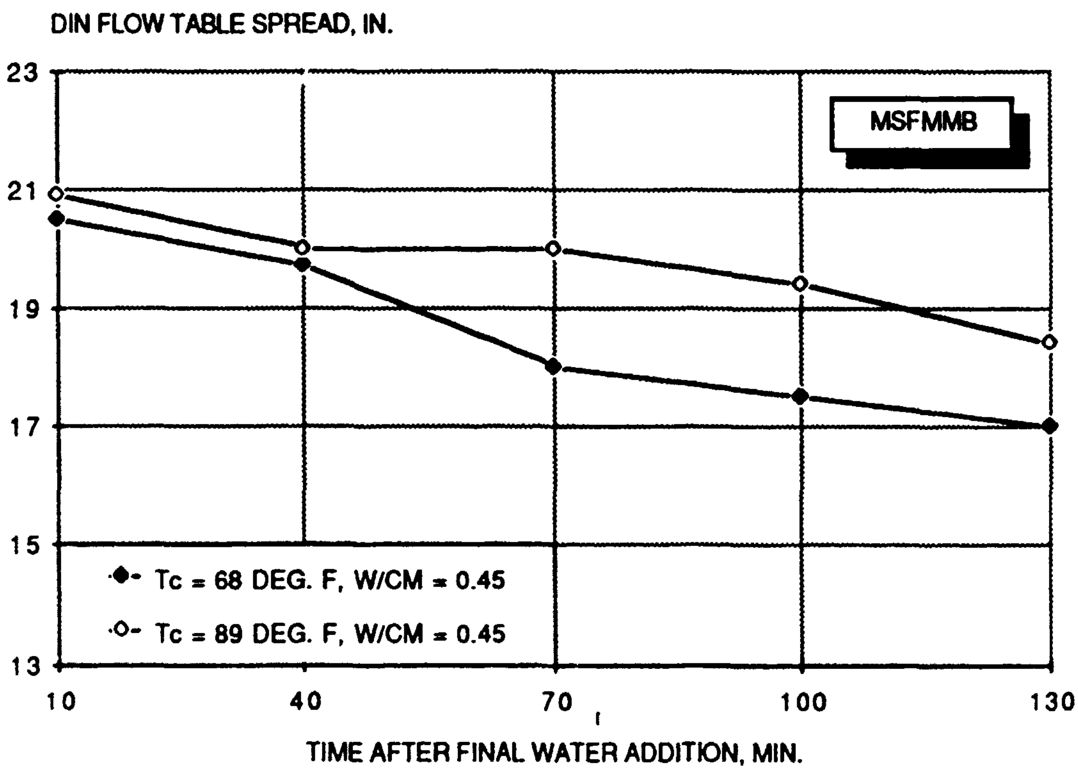
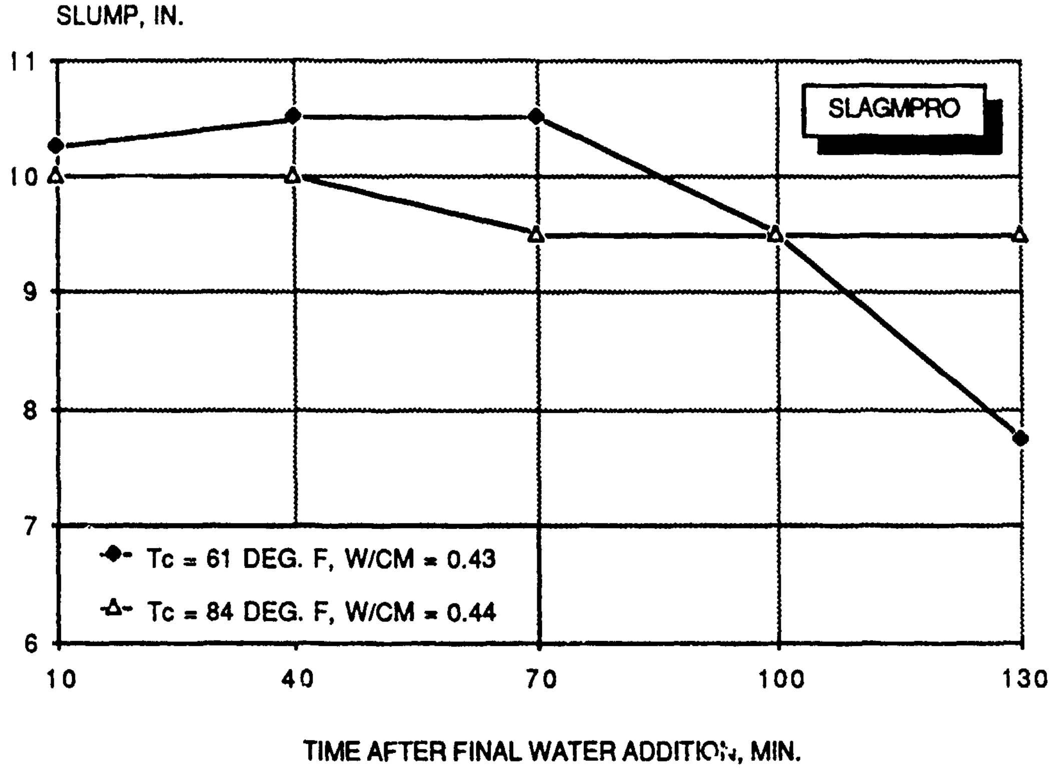


Fig. 18, 19--Slump and Flow Retentions of MSFMMB Mix at Various Temperatures



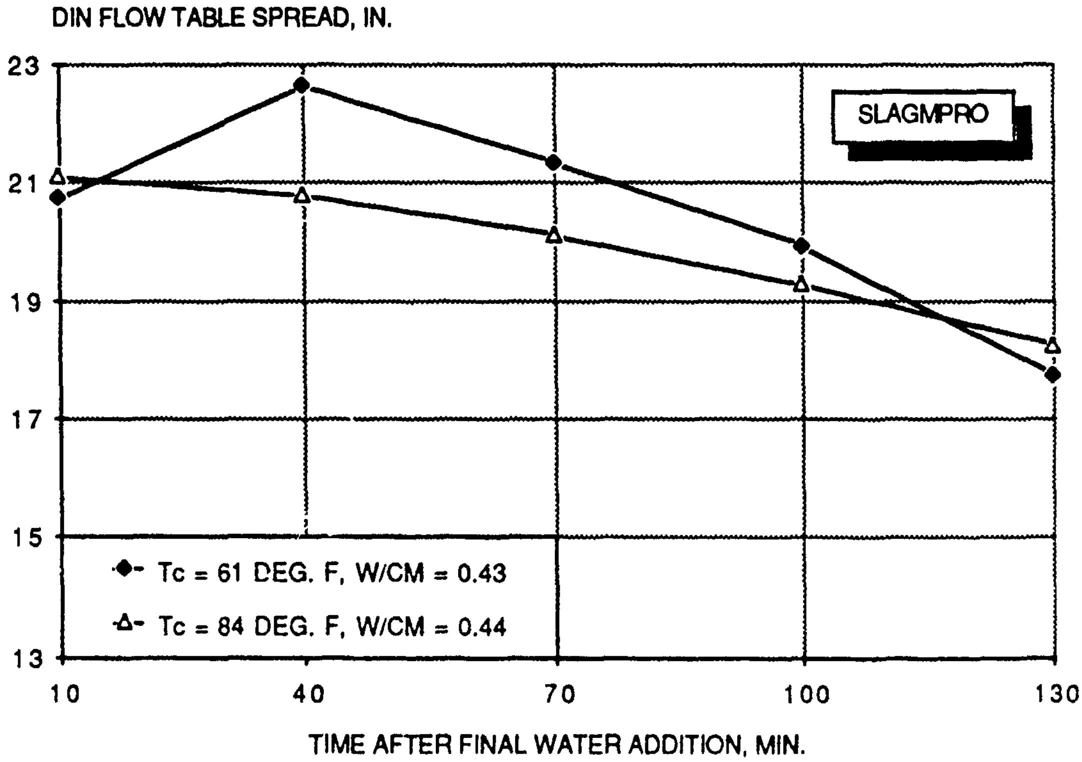
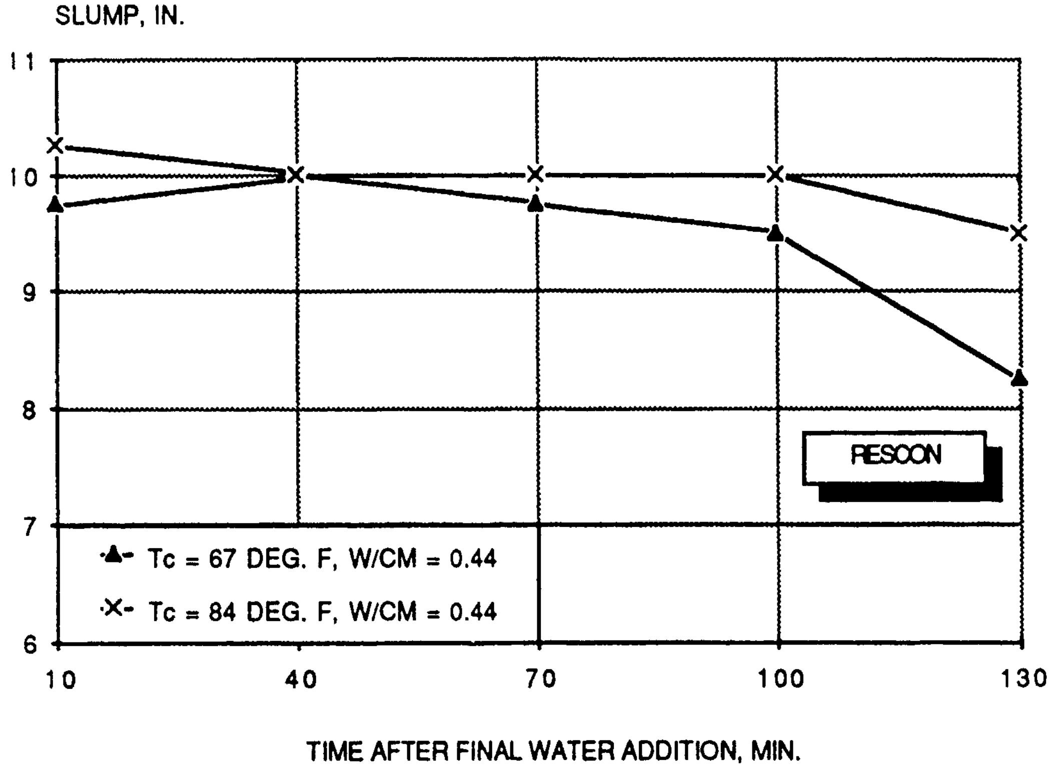


Fig. 20, 21--Slump and Flow Retentions of SLAGMPRO Mix at Various Temperatures



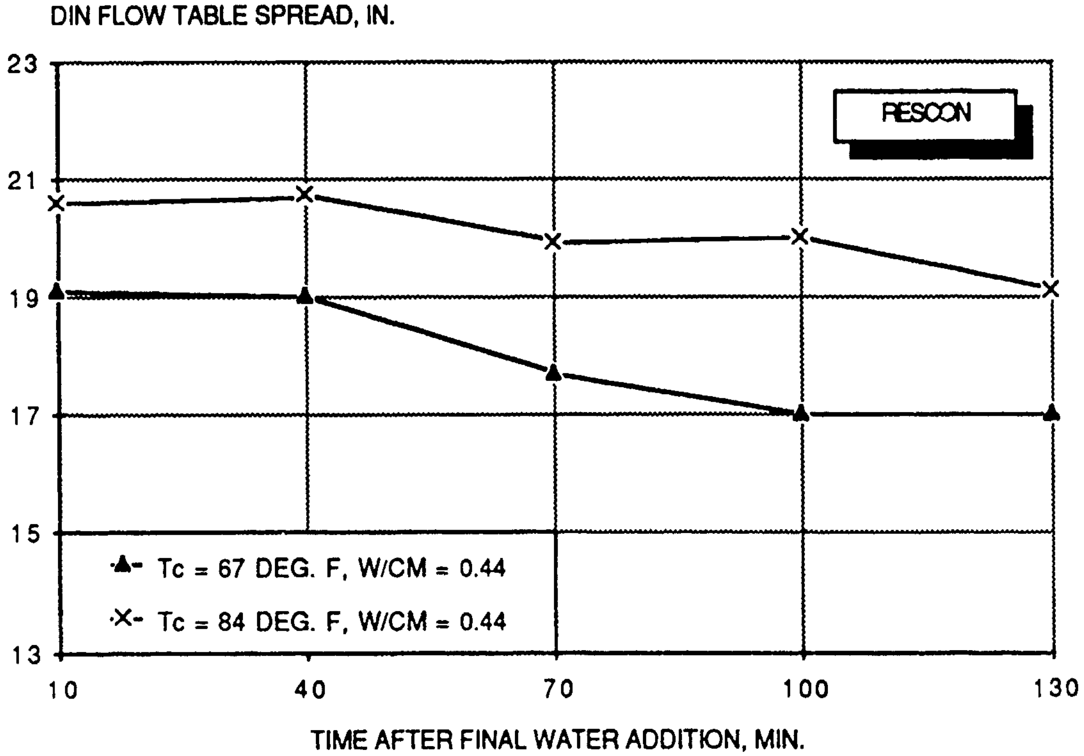
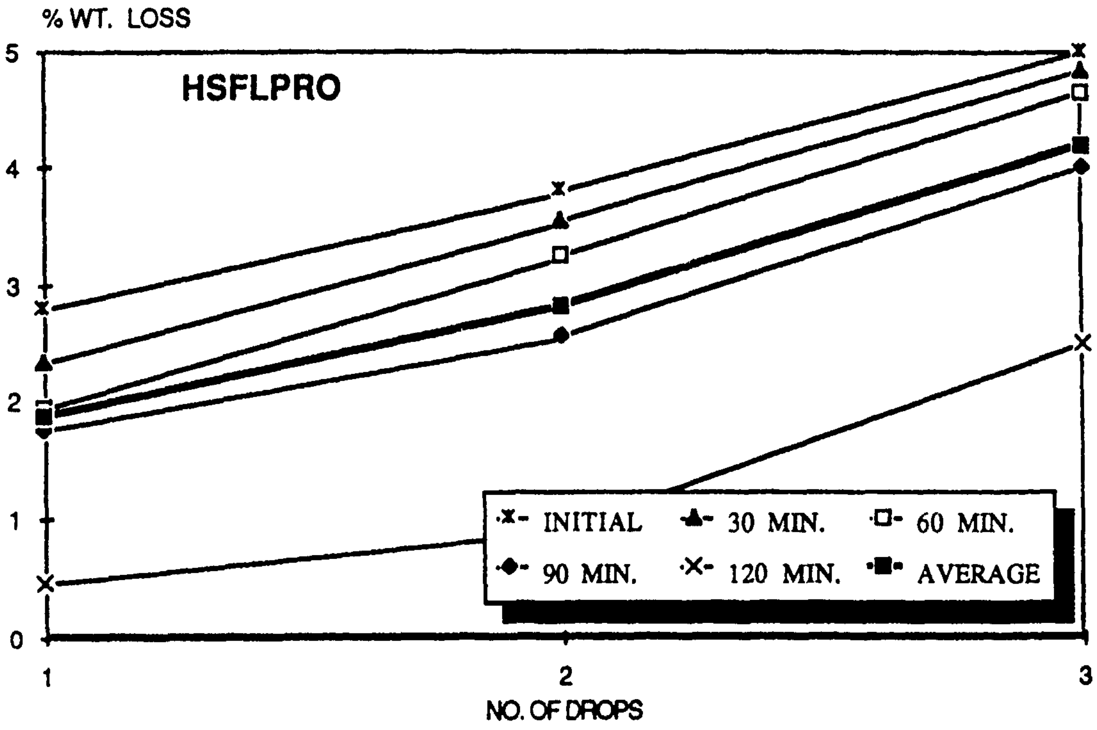


Fig. 22, 23--Slump and Flow Retentions of RESCON Mix at Various Temperatures



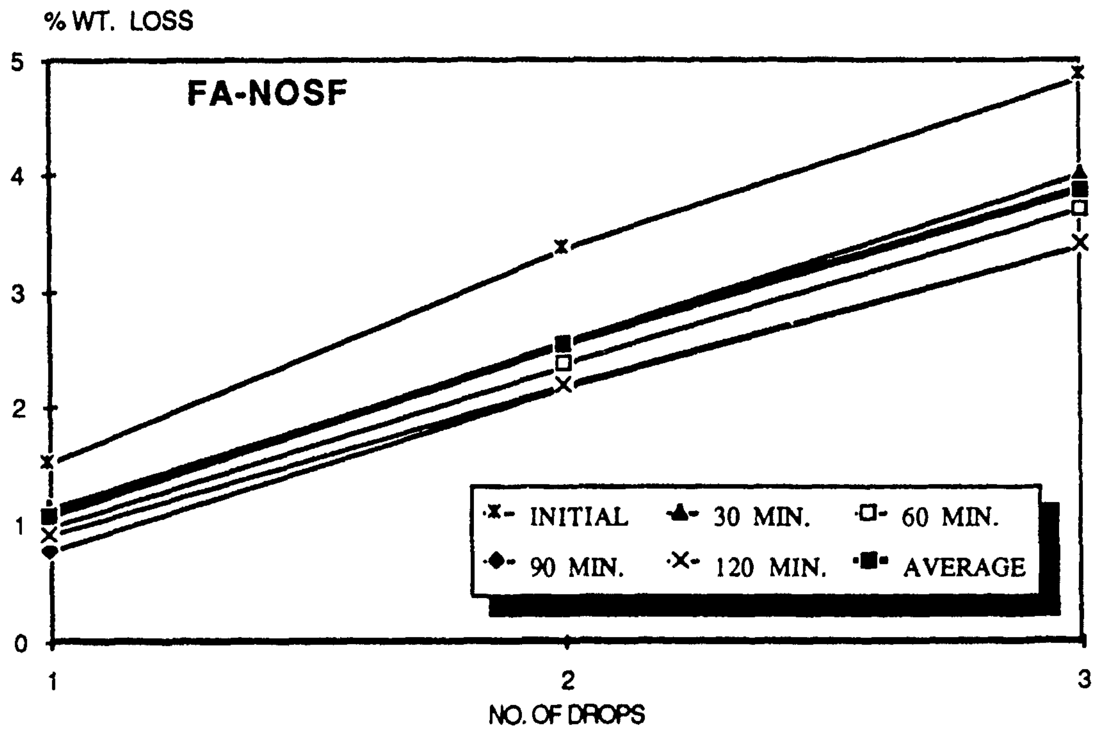
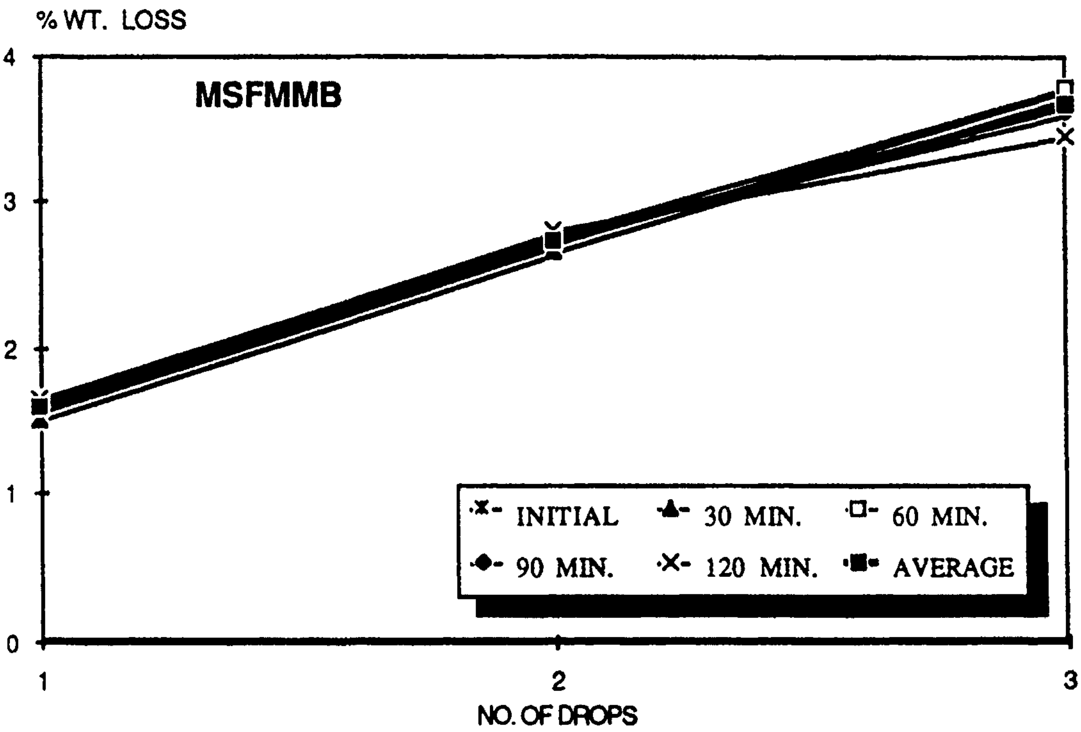


Fig. 24, 25--Water Erosion of the HSFLPRO and FA-NOSF Concretes



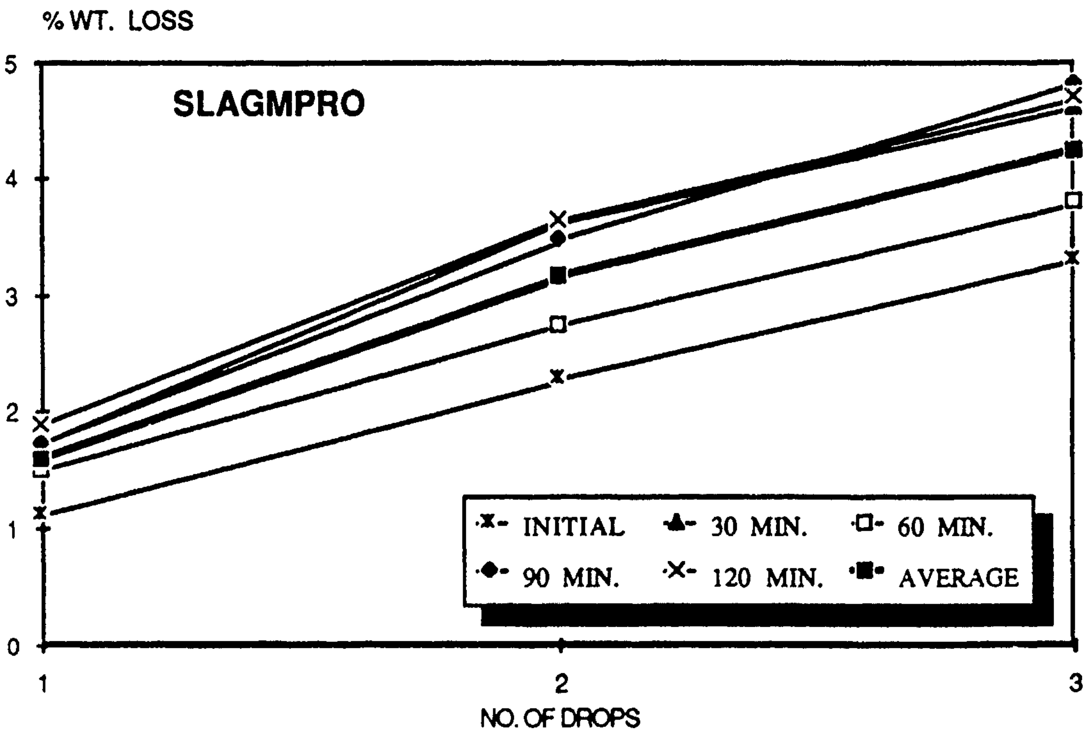


Fig. 26, 27--Water Erosion of the MSFMMB and SLAGMPRO Concretes

MIXTURE	HSFLPRO
W/CM	0.38
SLUMP	10.0 IN.
DIN FLOW TABLE	22.7 IN.

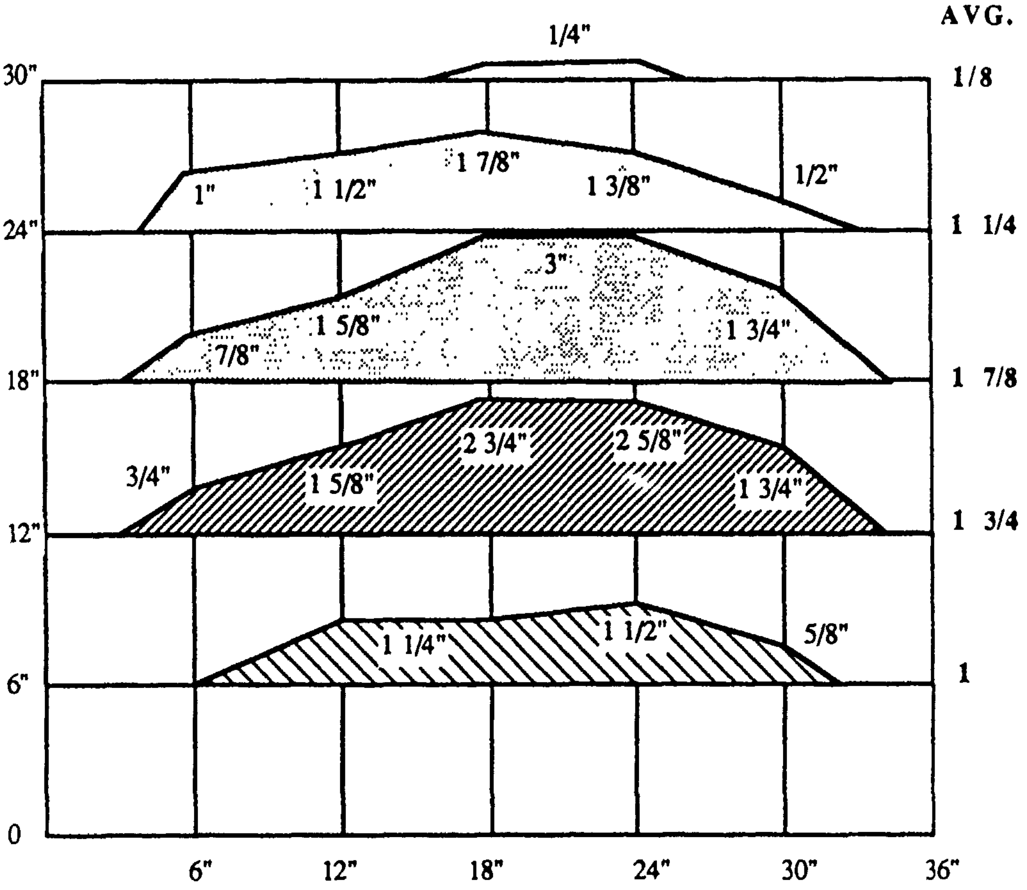


Fig. 28--Underwater Flow of the HSFLPRO Concrete

MIXTURE	MSFMPRO
W/CM	0.43
SLUMP	10.25 IN.
DIN FLOW TABLE	20.3 IN.

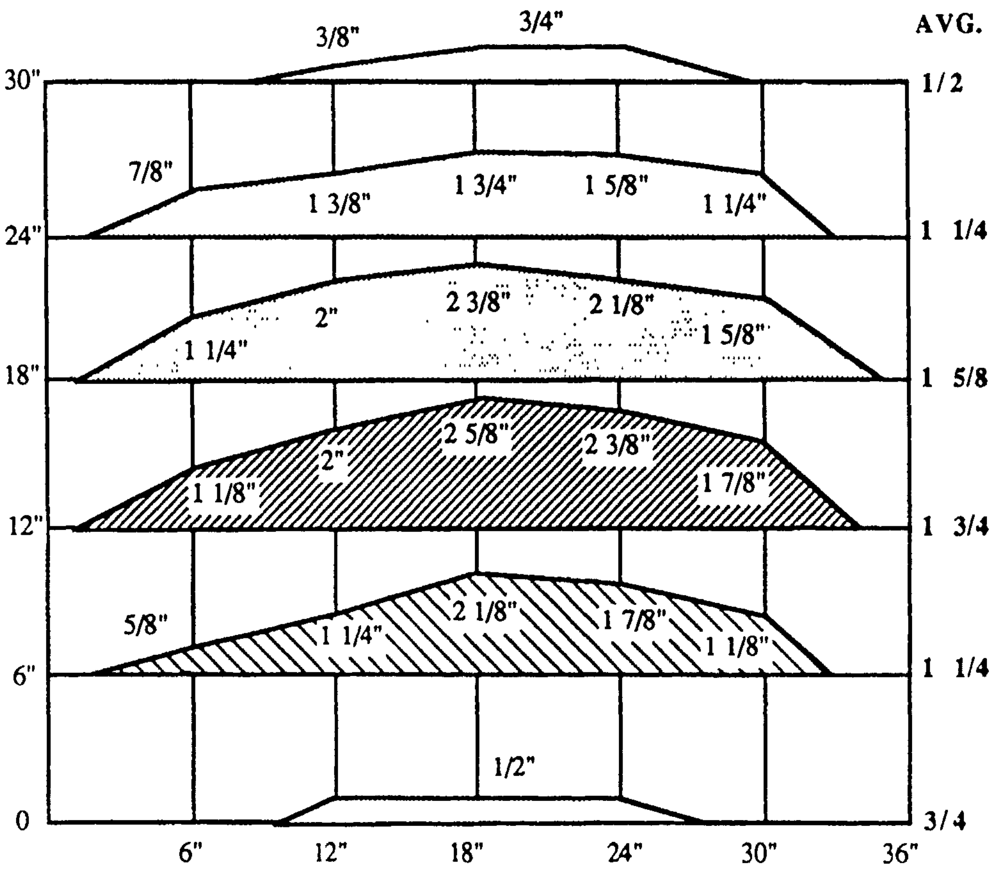


Fig. 29--Underwater Flow of the MSFMPRO Concrete

MIXTURE	LSFHPRO
W/CM	0.46
SLUMP	10.25 IN.
DIN FLOW TABLE	19.0 IN.

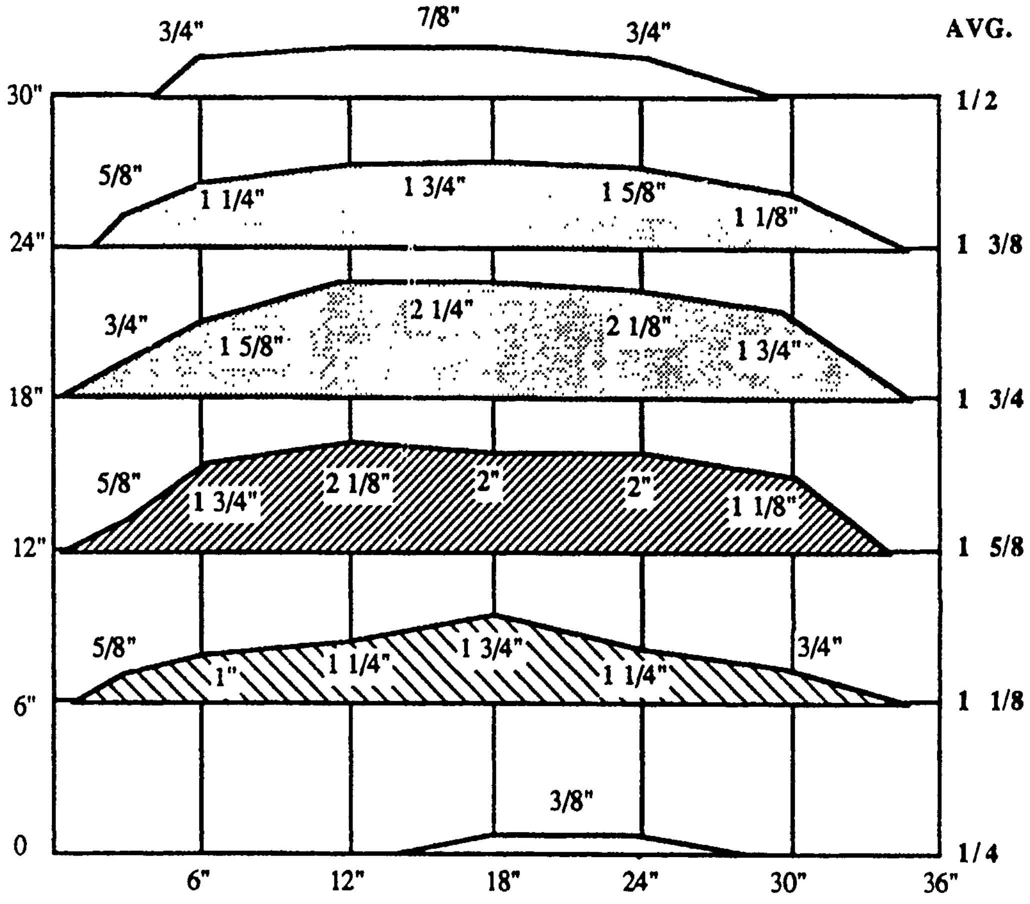


Fig. 30--Underwater Flow of the LSFHPRO Concrete

MIXTURE	MSFMMB
W/CM	0.45
SLUMP	9.0 IN.
DIN FLOW TABLE	19.5 IN.

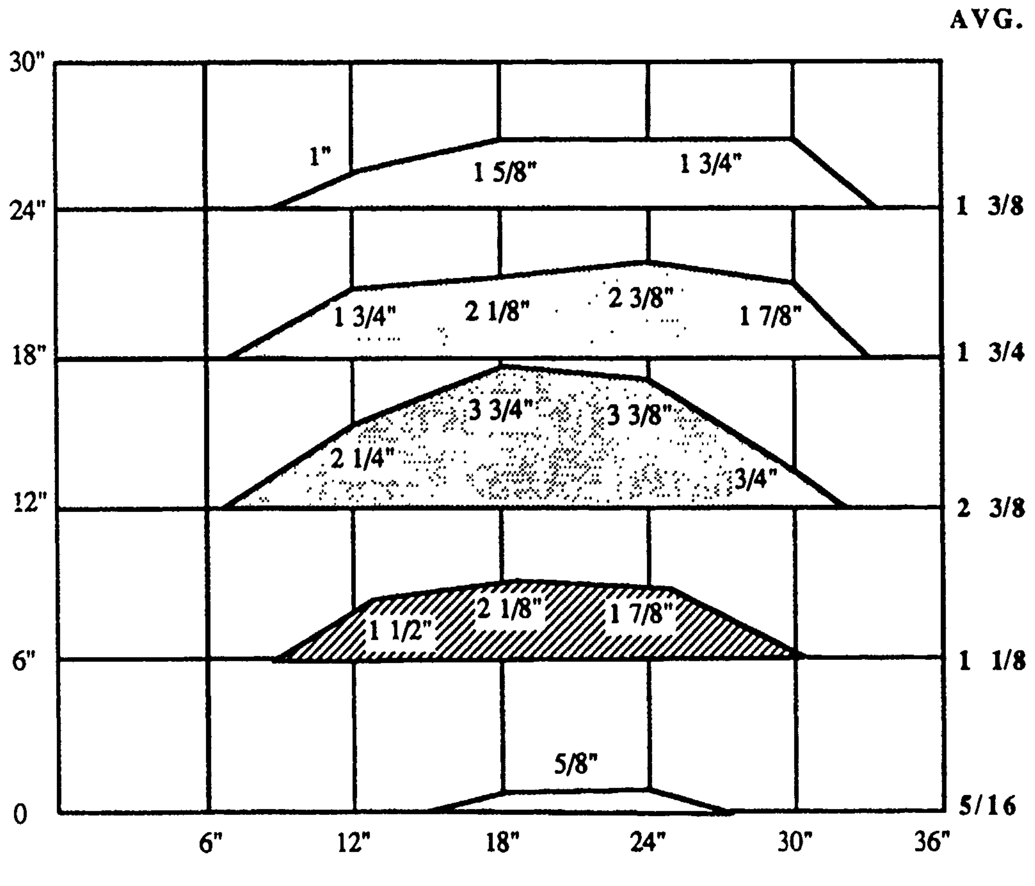


Fig. 31--Underwater Flow of the MSFMMB Concrete

MIXTURE	FAMPRO
W/CM	0.42
SLUMP	9.75 IN.
DIN FLOW TABLE	19.75 IN.

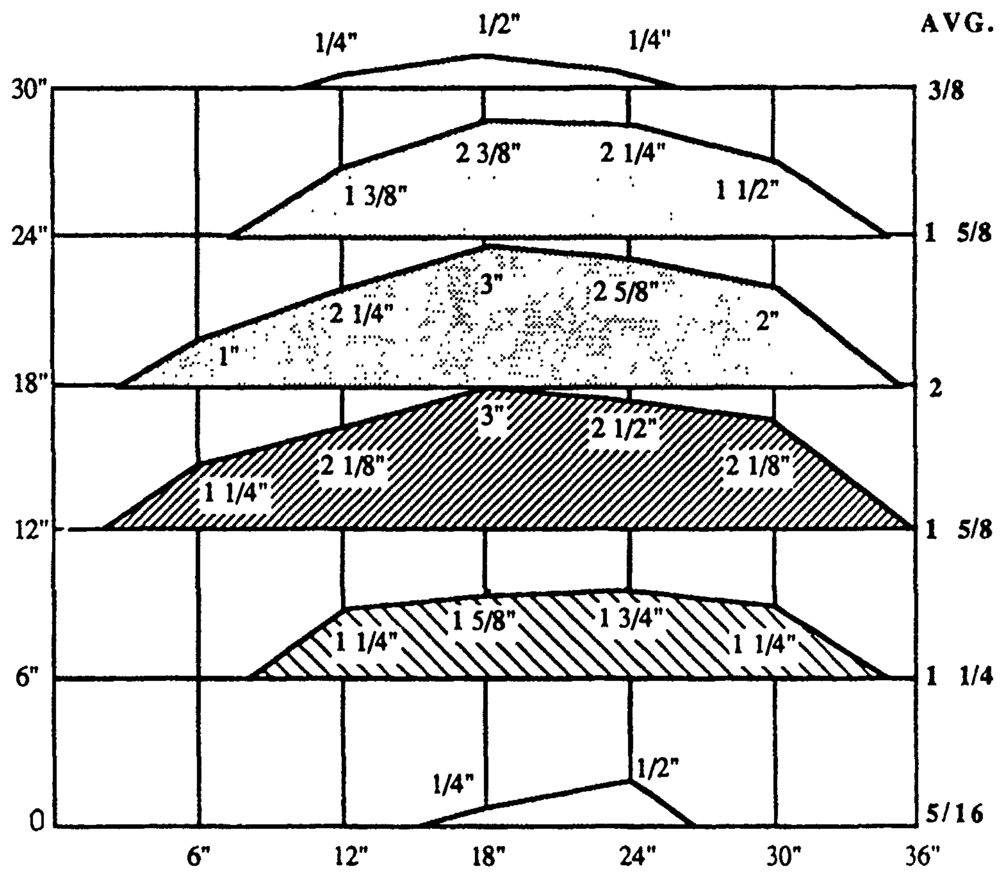


Fig. 32--Underwater Flow of the FAMPRO Concrete

Table 9. Rankings of Fluid Concretes Based on Compressive Strength

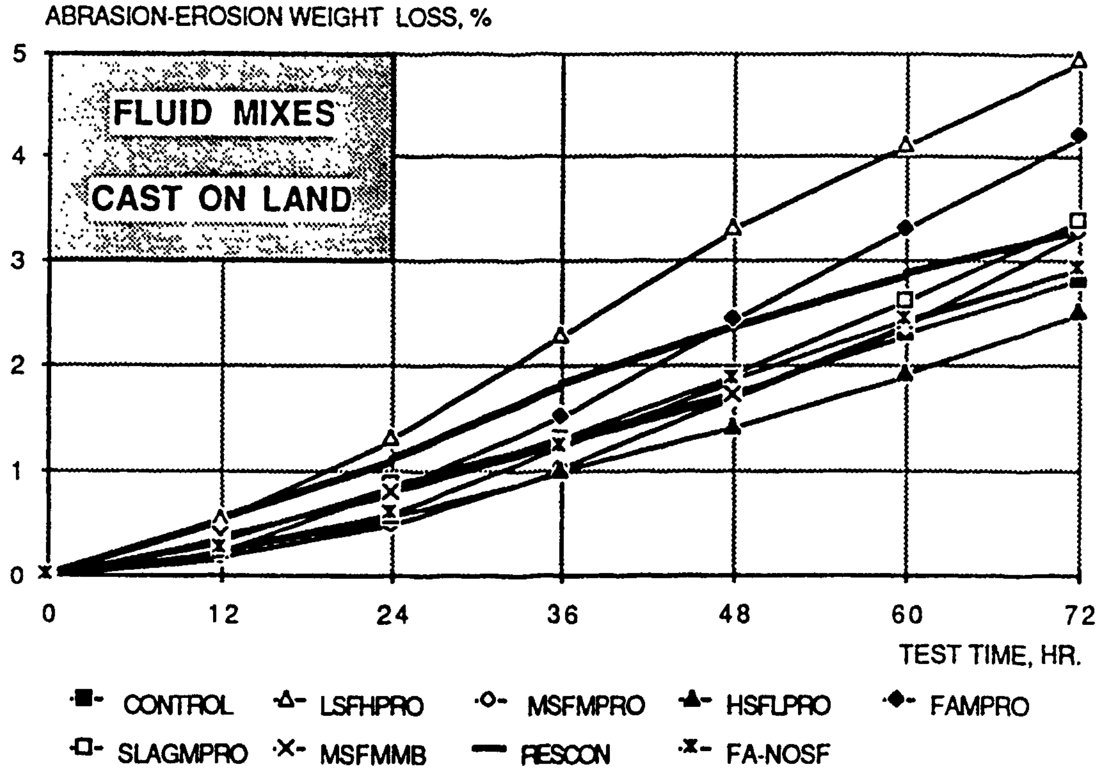
FINAL MIXTURE	W/CM	% AIR	7 D.	RANK	28 D.	RANK	56 D.	RANK
MOBILE CONTROL	0.36	3.25	6270	2	10525	2	11585	1
HSFLPRO	0.38	4	6350	1	10085	3	11240	2
MSFMPRO	0.42	4.25	5740	3	7910	6	9510	4
LSFHPRO	0.46	3.5	4765	8	6850	10	8065	8
MSFMMB	0.45	3.5	5485	5	8225	5	9035	5
SLAGMPRO	0.43	4.75	3780	10	8240	4	8630	6
FAMPRO	0.42	4.5	4730	9	7720	7	7635	11
FA-NOSF	0.41	3	5240	6	6915	9	7930	9
RESCON	0.44	2.5	4990	7	5610	11	8370	7
KELCO	0.46	3	3675	11	6920	8	7905	10
Z10-A	0.36	2.5	5610	4	10685	1	10740	3

Table 10. Rankings of Fluid Concretes Based on Splitting Tensile Strength

FINAL MIXTURE	W/CM	% AIR	7 D.	RANK	28 D.	RANK	56 D.	RANK
MOBILE CONTROL	0.36	3.25	690	1	920	1	1000	1
HSFLPRO	0.38	4	665	2	870	3	955	2
MSFMPRO	0.42	4.25	615	3	695	7	835	5
LSFHPRO	0.46	3.5	535	7	675	8	740	9
MSFMMB	0.45	3.5	595	4	770	6	820	7
SLAGMPRO	0.43	4.75	485	9	890	2	860	4
FAMPRO	0.42	4.5	595	4	790	5	825	6
FA-NOSF	0.41	3	455	10	535	11	560	11
RESCON	0.44	2.5	515	8	655	9	820	7
KELCO	0.46	3	355	11	570	10	620	10
Z10-A	0.36	2.5	560	6	855	4	865	3

Table 11. Rankings of Fluid Concretes Based on Flexural Strength

FINAL MIXTURE	W/CM	% AIR	56 D.	RANK
MOBILE CONTROL	0.36	3.25	1180	1
HSFLPRO	0.38	4	1105	2
MSFMPRO	0.42	4.25	1080	3
LSFHPRO	0.46	3.5	880	6
MSFMMB	0.45	3.5	910	5
SLAGMPRO	0.43	4.75	1030	4
FAMPRO	0.42	4.5	850	7
FA-NOSF	0.41	3	--	--
RESCON	0.44	2.5	--	--
KELCO	0.46	3	750	8
Z10-A	0.36	2.5	--	--



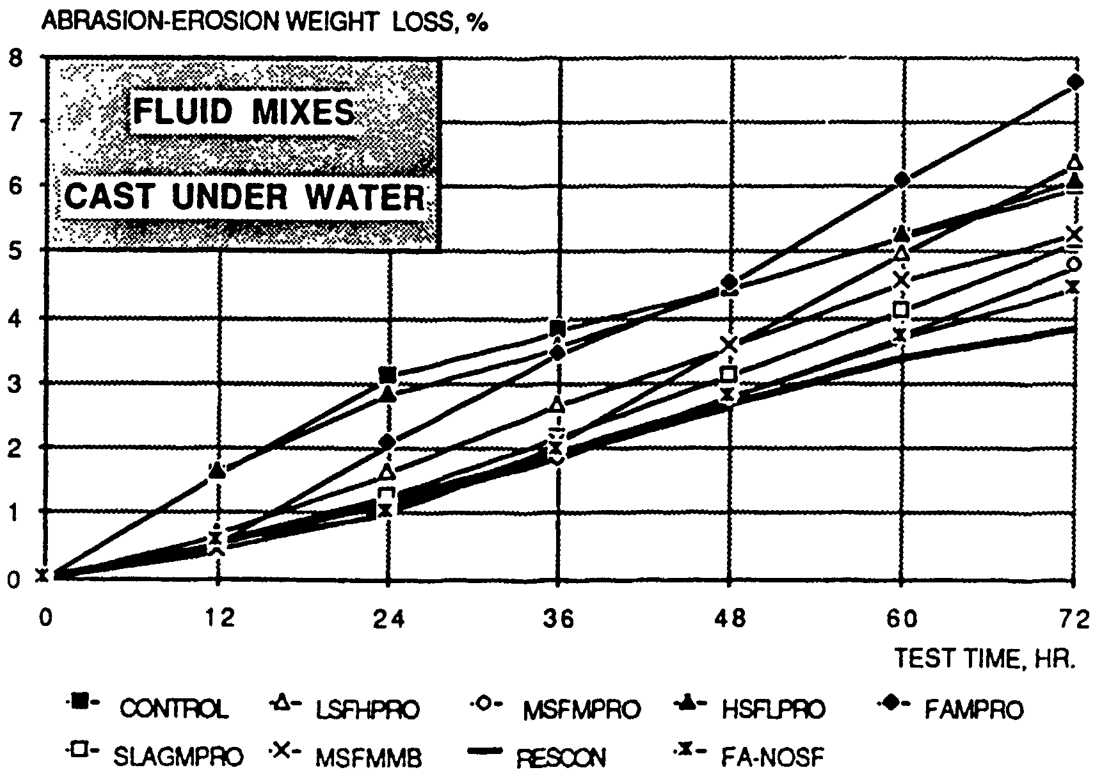


Fig. 33, 34--56 Day Abrasion-erosion Results of Concretes Cast Above and Under Water

Appendix D - Repair of Small and Relatively Shallow Scour Holes

Fig. 35--Picture of "Old" Concrete Base

Fig. 36--Picture of the Roughened Surface of "Old" Concrete

Fig. 37--Picture of the Vertical Tremie Pipe

Fig. 38--Tremie Pipe Submerged in Water

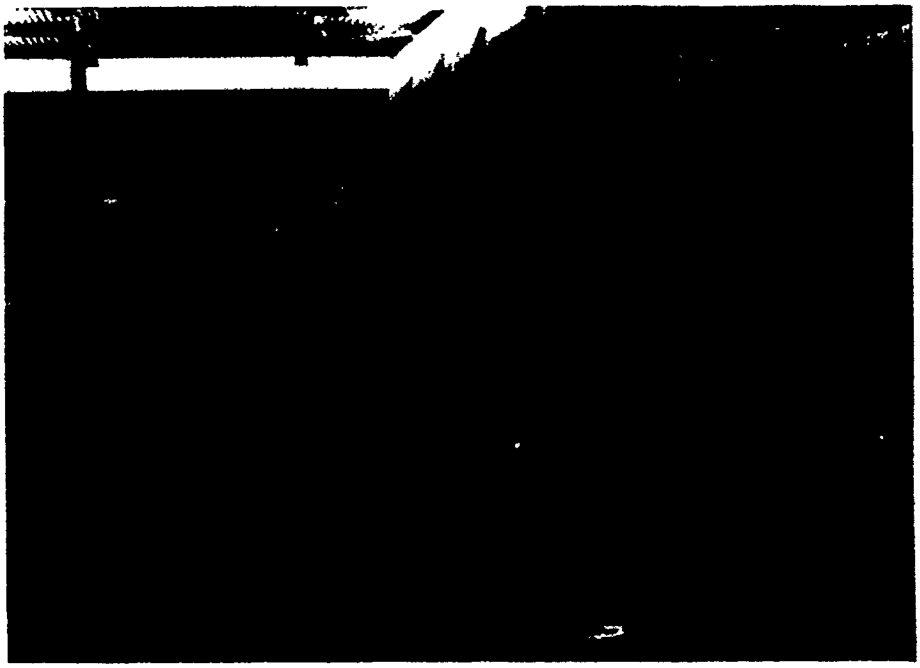


Fig. 39--Picture of the Inclined Tremie Pipe

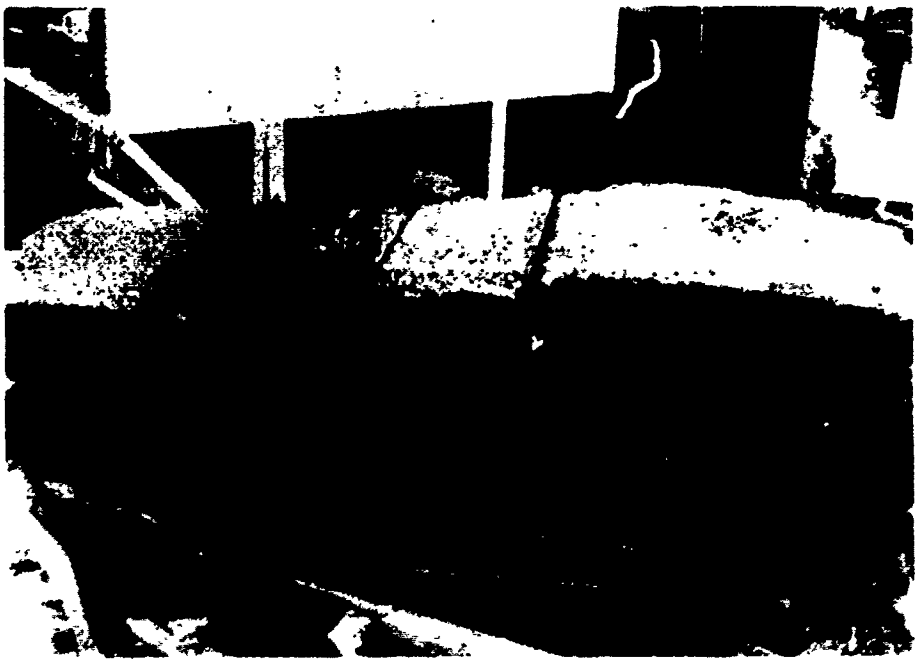


Fig. 40--Picture of Stripped Slab with Dividers Removed

Fig. 41--Picture of the CONTROL-TREMIE Slab

Fig. 42--End Segment of the CONTROL-TREMIE Slab

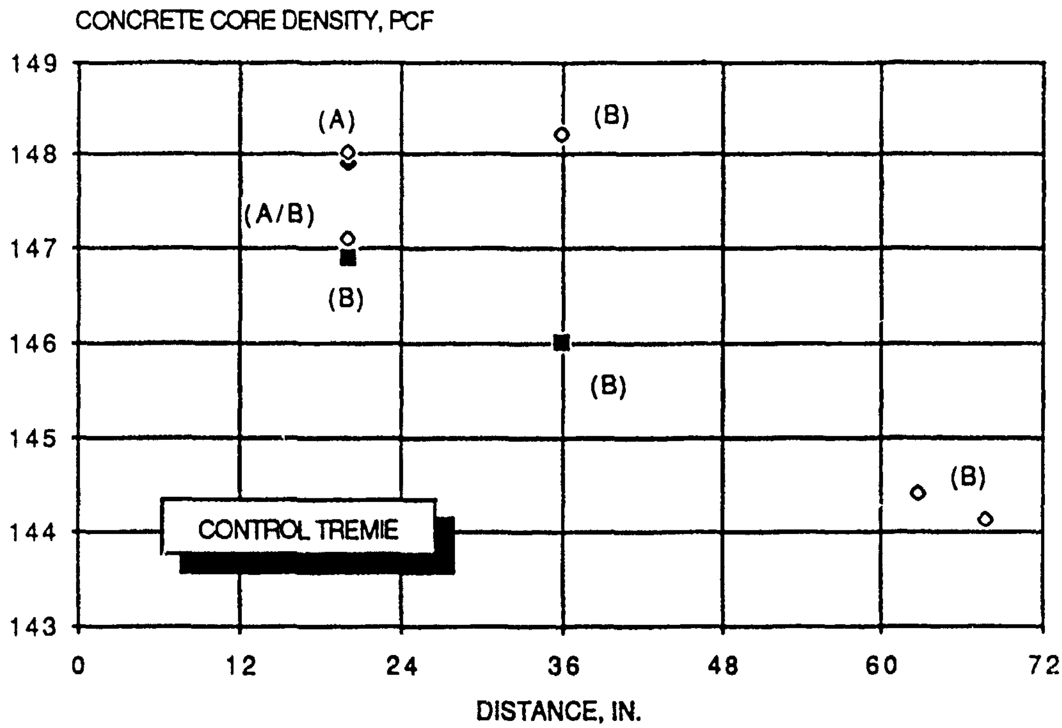


Fig. 43--Unit Weight Values along the CONTROL-TREMIE Slab

Table 12. Density Results of the CONTROL-TREMIE Cores

MIX METHOD	CONTROL TREMIE						
CUT CORE DESCRIPTIONS	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	DENSITY CUT CORE, PCF	% DENSITY INCREASE CUT/UNCUT	% OF AVG. CONTROL DENSITIES
MIX A CONTROL				103	149.8		100
MIX B CONTROL				103	149.7		100
5.32" B	8	20	TOP	103	146.9	0.14	98.1
7.85" A	8	20	TOP	103	147.9	0	98.8
3.1" A, 7.3" B	21	20	TOP	103	147.1	0.14	98.2
6.6" A	21	20	TOP	103	148	0	98.8
5.4" B	9	36	TOP	103	146	0.21	97.5
4.95" B	21	36	TOP	103	148.2	0.41	99
2.95" B	26	63	TOP	103	144.4	1.4	96.4
2.8" B	26	68	TOP	103	144.1	1.27	96.2

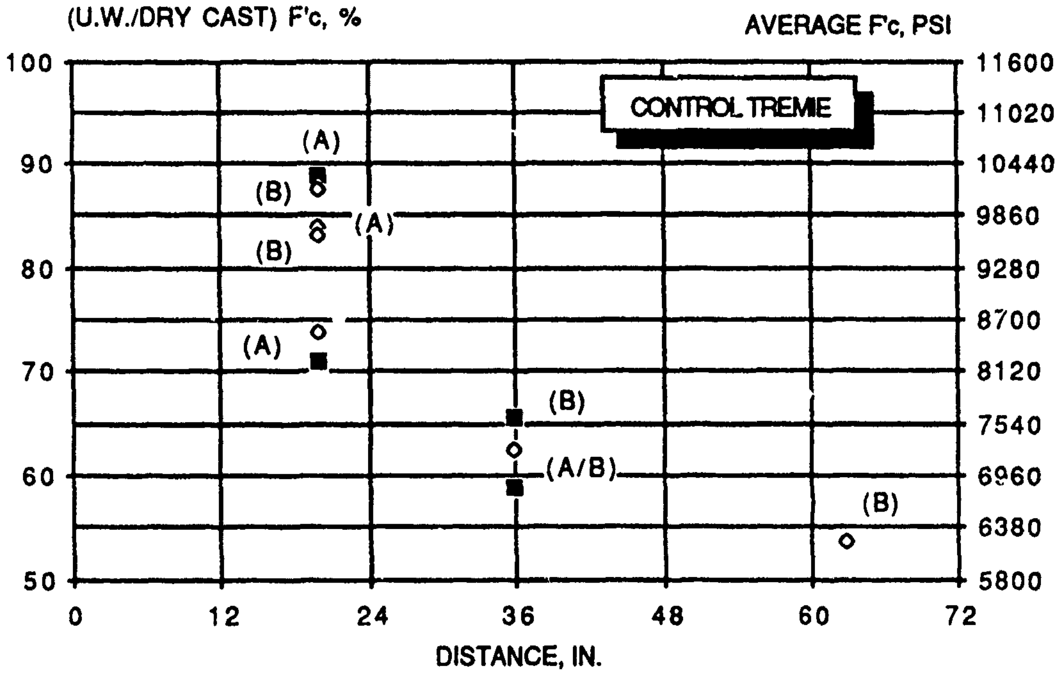


Fig. 44--Compressive Strength Values along the CONTROL-TREMIE Slab

Table 13. Compressive Strength Results of the CONTROL-TREMIE Cores

MIXTURE METHOD	CONTROL TREMIE							
CAPPED CORE DESCRIPTIONS	COORDINATES X, IN.	Y, IN.	CORED FROM	AGE, DAYS	L/D	ADJ. FACTOR	F'c, PSI	% CONT. A OR B F'c
MIX A CONTROL				109			12095	100
MIX B CONTROL				109			10980	100
5.52" B	8	20	TOP	109	1.978	0.988	9685	88.2
4.78" A	8	20	TOP	109	1.713	0.977	8565	70.8
3.58" A	8	20	TOP	109	1.283	0.934	10740	88.8
4.71" B	21	20	TOP	109	1.688	0.975	9600	87.4
2.9" A	21	20	TOP	109	1.039	0.921	8900	73.6
6.9" A	21	20	MIDDLE	109	2.473	1	10140	83.8
3.01" B	21	20	MIDDLE	109	1.079	0.888	9120	03.1
5.6" B	9	36	TOP	109	2	1	7180	65.4
1.25" A, 1.4" B	9	36	MIDDLE	109	1	0.87	6765	58.6
1.5" A, 1.5" B	21	36	MIDDLE	109	1.075	0.888	7190	62.3
3.1" B	26	63	TOP	109	1.111	0.897	5865	53.4

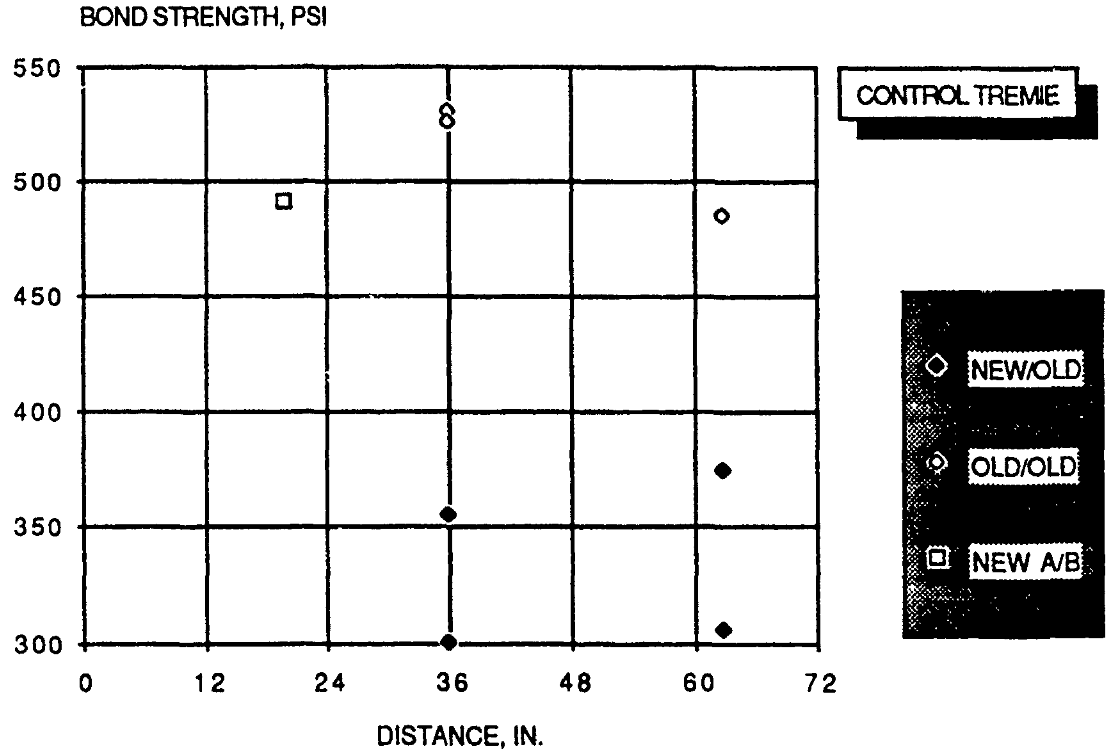


Fig. 45--Bond Strength Values along the CONTROL-TREMIE Slab

Table 14. Bond Strength Results of the CONTROL-TREMIE Cores

MIX METHOD		CONTROL TREMIE			AGE:	109 DAYS
CUT CORE DESCRIPTIONS	BONDED MAT'S	COORDINATES X, IN.	COORDINATES Y, IN.	BOND STRENGTH, PSI	% OF MIX	COMMENTS
5.1" OLD, 3.2" A,B	A / OLD	9	36	300	55 OLD	@ BOND, FLAT
5.1" OLD, 5.1" A,B	A / OLD	21	36	355	67 OLD	THRU. A, JAGGED
5.1" OLD, 2" B	B / OLD	21	63	305	63 OLD	@ BOND
4.8" OLD, 3" B	B / OLD	9	63	375	----	@ BOND, SEMI-FLAT
5.1" OLD	OLD/OLD	9	36	530	----	JAGGED, ANGULAR
5.1" OLD	OLD/OLD	21	36	525	----	JAGGED, ANGULAR
5.1" OLD	OLD/OLD	21	63	485	----	JAGGED, ANGULAR
3.5" A, 7" B	A / B	21	20	490	----	THROUGH A & B

Fig. 46--Picture of the MSFMPRO-TREMIE Slab

Fig. 47--Section II of the MSFMPRO-TREMIE Slab

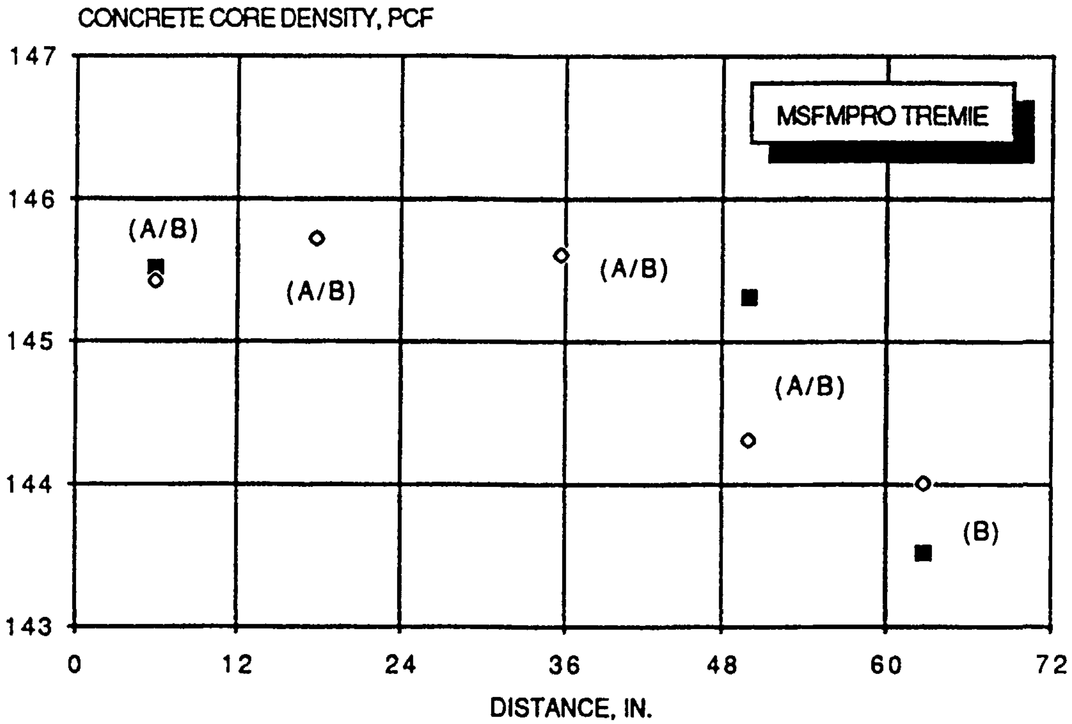


Fig. 48--Unit Weight Values along the MSFMPRO-TREMIE Slab

Table 15. Density Results of the MSFMPRO-TREMIE Cores

MIX METHOD	MSFMPRO TREMIE						
CUT CORE DESCRIPTIONS	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	DENSITY CUT CORE, PCF	% DENSITY INCREASE CUT/UNCUT	% OF AVG. CONTROL DENSITIES
MIX A CONTROL				104	148.3		100
MIX B CONTROL				104	148.7		100
2.1" A, 4.75" B	9.5	6	TOP	107	145.5	0.21	98
4.2" A, 4.7" B	20.5	6	TOP	107	145.4	0	97.9
4.15" A, 4.4" B	20.5	18	TOP	107	145.7	0.14	98.1
5.65" A, 3" B	20.5	36	TOP	107	145.6	0	98
2.65" A, 2" B	9.5	50	TOP	107	145.3	0.07	97.8
1.8" A, 1.85" B	20.5	50	TOP	107	144.3	0	97.2
5.8" B	5	63	ACROSS	107	143.5	0.14	96.6
6.05" B	25	63	ACROSS	107	144	0.14	97

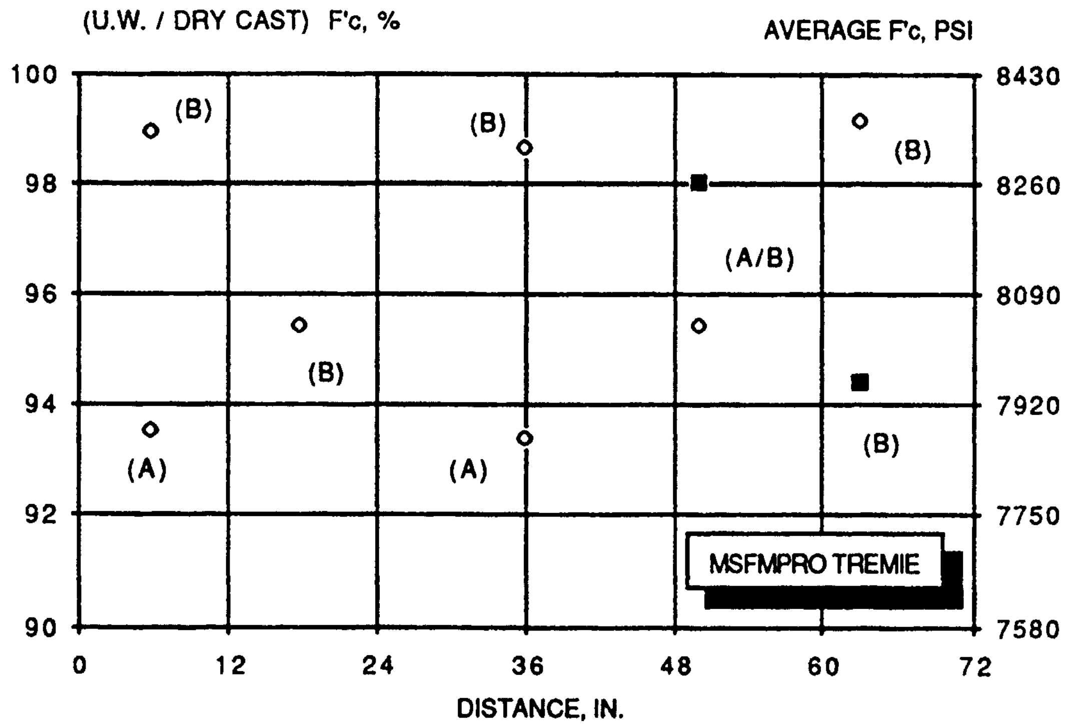


Fig. 49--Compressive Strength Values along of the MSFMPRO-TREMIE Slab

Table 16. Compressive Strength Results of MSFMPRO-TREMIE Cores

MIXTURE METHOD	MSFMPRO TREMIE							
CAPPED CORE DESCRIPTIONS	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	L/D	ADJ. FACTOR	F'c, PSI	% CONT. A OR B F'c
MIX A CONTROL				103			8415	100
MIX B CONTROL				103			8440	100
4.12" A	20.5	6	TOP	110	1.532	0.977	7895	93.5
4.03" B	20.5	6	TOP	110	1.498	0.96	8445	98.9
4.5" B	20.5	18	TOP	110	1.673	0.974	8055	95.4
5.42" A	20.5	36	TOP	110	2.015	1	7885	93.4
3" B	20.5	36	TOP	110	1.115	0.898	8420	98.6
1.9" A, 2.4" B	20.5	50	ACROSS	110	1.978	0.998	8095	95.4
2.3" A, 2.3" B	9.5	50	ACROSS	110	1.71	0.977	8320	98
6" B	20.5	63	ACROSS	110	2.23	1	8465	99.1
6.2" B	9.5	63	ACROSS	110	2.3	1	8060	94.4

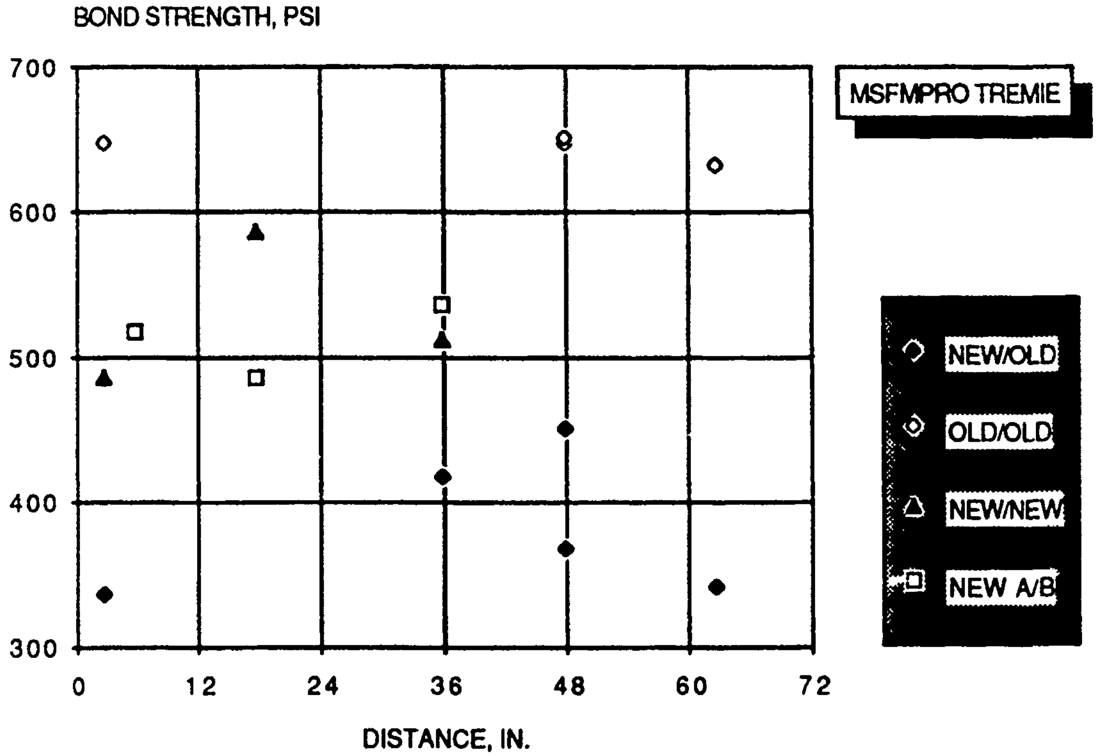


Fig. 50--Bond Strengths along the MSFMPRO-TREMIE Slab

Table 17. Bond Strengths of the MSFMPRO-TREMIE Slab

MIX METHOD	MSFMPRO TREMIE				AGE:	110 DAYS
CUT CORE DESCRIPTIONS	BONDED MAT'S	COORDINATE X, IN.	COORDINATE Y, IN.	BOND STRENGTH, PSI	% OF MIX	COMMENTS
4.3" OLD, 6.7" A	A / OLD	20	3	335	52 OLD, 69 A	THROUGH A & B
5" OLD, 4" A	A / OLD	10	36	415	81 A	JAGGED
4.25" OLD, 5" A & B	A / OLD	10	48	365	57 OLD	@ BOND, FLAT
5" OLD, 4.5" A & B	A / OLD	21	48	450	69 OLD	@ BOND, FLAT
5" OLD, 6.75" B	B / OLD	21	63	340	54 OLD	@ BOND, FLAT
4.3" OLD	OLD/OLD	20	3	645	----	JAGGED, ANGULAR
4.25" OLD	OLD/OLD	10	48	645	----	JAGGED, ANGULAR
5" OLD	OLD/OLD	21	48	650	----	JAGGED, ANGULAR
5" OLD	OLD/OLD	21	63	630	----	JAGGED, ANGULAR
6.7" A	A / A	20	3	485	----	JAGGED, ANGULAR
4" A	A / A	10	36	510	----	JAGGED, ANGULAR
4.4" B	B / B	21	18	585	----	JAGGED, ANGULAR
4.2" A, 5.5" B	A / B	21	6	515	----	1/2 IN A, 1/2 IN B
4.6" A, 4.4" B	A / B	21	18	485	----	1/2 IN A, 1/2 IN B
5.7" A, 3" B	A / B	21	36	535	----	THROUGH A & B

Fig. 51--Section II of the HSFLPRO-TREMIE Slab

Fig. 52--Section IV of the HSFLPRO-TREMIE Slab

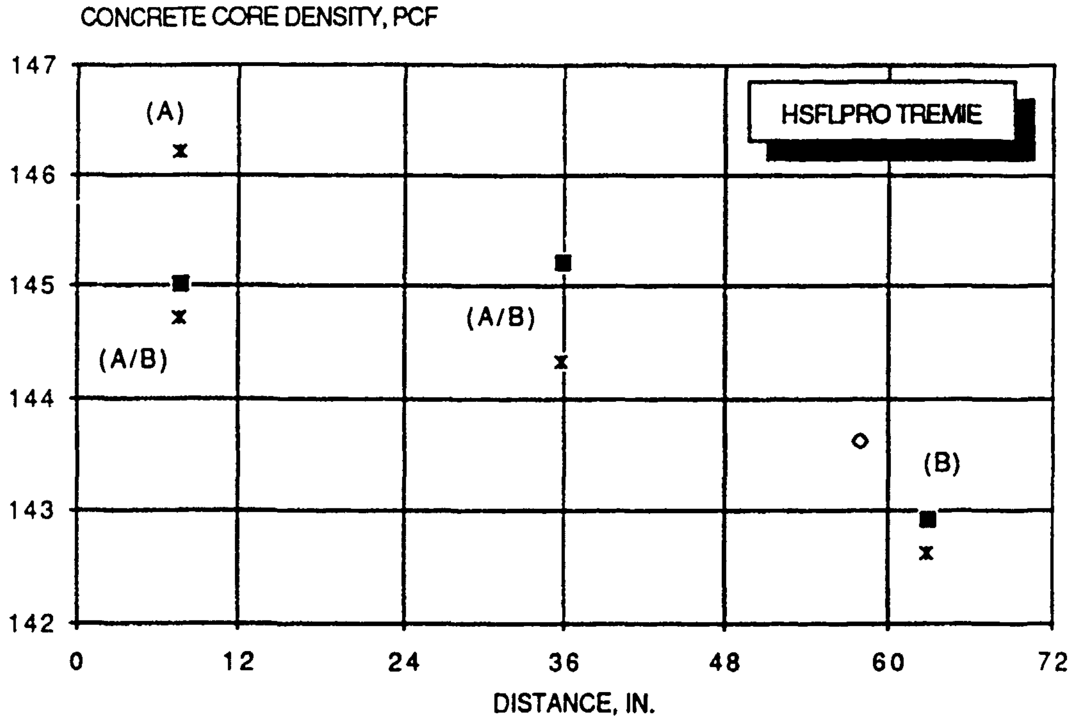


Fig. 53--Unit Weight along the HSFLPRO-TREMIE Slab

Table 18. Density Results of the HSFLPRO-TREMIE Cores

MIX METHOD	HSFLPRO TREMIE						
CUT CORE DESCRIPTIONS	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	DENSITY CUT CORE, PCF	% DENSITY INCREASE CUT/UNCUT	% OF AVG. CONTROL DENSITIES
MIX A CONTROL				99		151.1	100
MIX B CONTROL				99		150.5	100
4.6" A, 3.5" B	12	8	TOP	99	145	0.07	96.2
2" A, 2.35" B	18	8	TOP	99	144.7	0.21	96
3.82" A	18	8	TOP	99	146.2	0.07	96.9
1.5" A, 2.2" B	9	36	TOP	99	145.2	0.84	96.3
3" A, 2" B	15	36	TOP	99	144.3	0.07	95.7
5.9" B	28	58	TOP	99	143.6	1.92	95.2
6.55" B	4	63	TOP	99	142.9	2.14	94.8
5" B	15	63	TOP	99	142.6	0.42	94.6

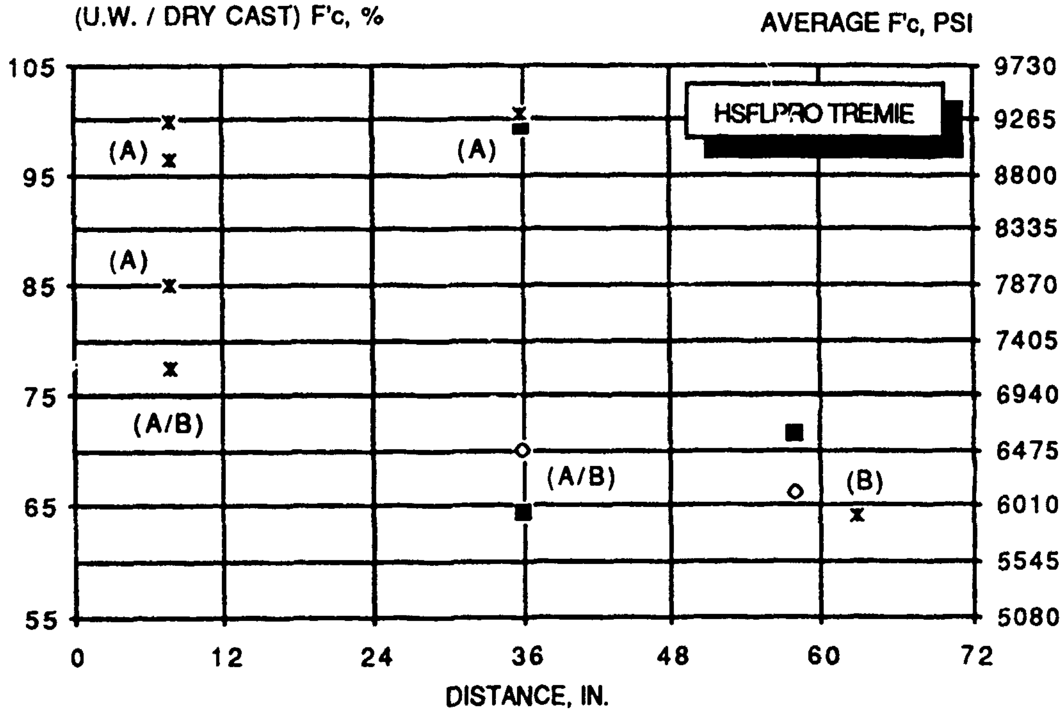


Fig. 54--Compressive Strength Values along the HSFLPRO-TREMIE Slab

Table 19. Compressive Strength Results of HSFLPRO-TREMIE Cores

MIXTURE METHOD	HSFLPRO TREMIE							
CAPPED CORE DESCRIPTIONS	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	L/D	ADJ. FACTOR	F'c, PSI	% CONT. A OR B F'c
MIX A CONTROL				100			9260	100
MIX B CONTROL				100			9265	100
2.4" A, 2.4" B	18	8	TOP	100	1.72	0.978	7150	77.2
4.21" A	18	8	MIDDLE	100	1.509	0.961	8910	96.2
4.8" A	12	8	TOP	100	1.72	0.978	9210	99.5
4.55" A	12	8	MIDDLE	100	1.631	0.97	7860	84.8
3.72" A	9	36	MIDDDLE	100	1.333	0.94	9195	99.2
3.65" A	15	36	MIDDLE	100	1.308	0.937	9305	100.4
1.7" A, 2.4" B	9	36	TOP	100	1.469	0.956	5960	64.3
2" A, 2.5" B	21	36	TOP	100	1.204	0.919	6485	70
6.1" B	28	58	TOP	100	2.183	1	6115	66
3.38" B	12	58	TOP	100	1.211	0.921	6625	71.5
5.24" B	15	63	TOP	100	1.878	0.99	5910	63.8

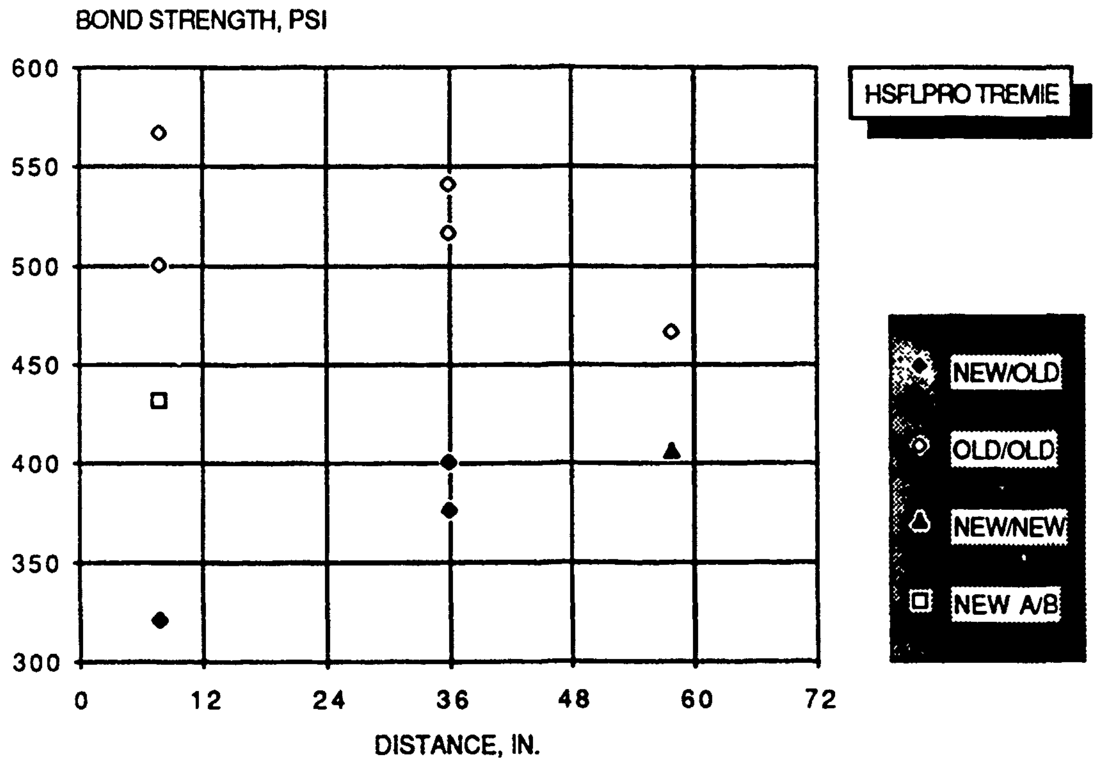


Fig. 55--Bond Strength Values along the HSFLPRO-TREMIE Slab

Table 20. Bond Strength Results of the HSFLPRO-TREMIE Cores

MIX METHOD		HSFLPRO TREMIE			AGE:	100 DAYS
CUT CORE DESCRIPTIONS	BONDED MAT'S	COORDINATES X, IN.	COORDINATES Y, IN.	BOND STRENGTH, PSI	% OF MIX	COMMENTS
5.2" OLD, 5.1" A	A / OLD	18	8	320	64 OLD	@BOND
4.8" OLD, 3.7" A	A / OLD	9	36	400	74 OLD	80% @ BOND
4.7" A, 3.5" A	A / OLD	15	36	375	73 OLD	50% @ BOND
5" OLD	OLD/OLD	12	8	565	----	JAGGED, ANGULAR
5.2" OLD	OLD/OLD	18	8	500	----	JAGGED, ANGULAR
4.8" OLD	OLD/OLD	9	36	540	----	JAGGED, ANGULAR
4.7" OLD	OLD/OLD	15	36	515	----	JAGGED, ANGULAR
5.1" OLD	OLD/OLD	12	58	465	----	JAGGED, ANGULAR
6" B	B / B	12	58	405	----	JAGGED, ANGULAR
4.6" A, 3.5" B	A / B	12	8	430	----	20% IN A, 80% IN B

Fig. 56--Picture of the SLAGMPRO-TREMIE Slab

Fig. 57--Section III of the SLAGMPRO-TREMIE Slab

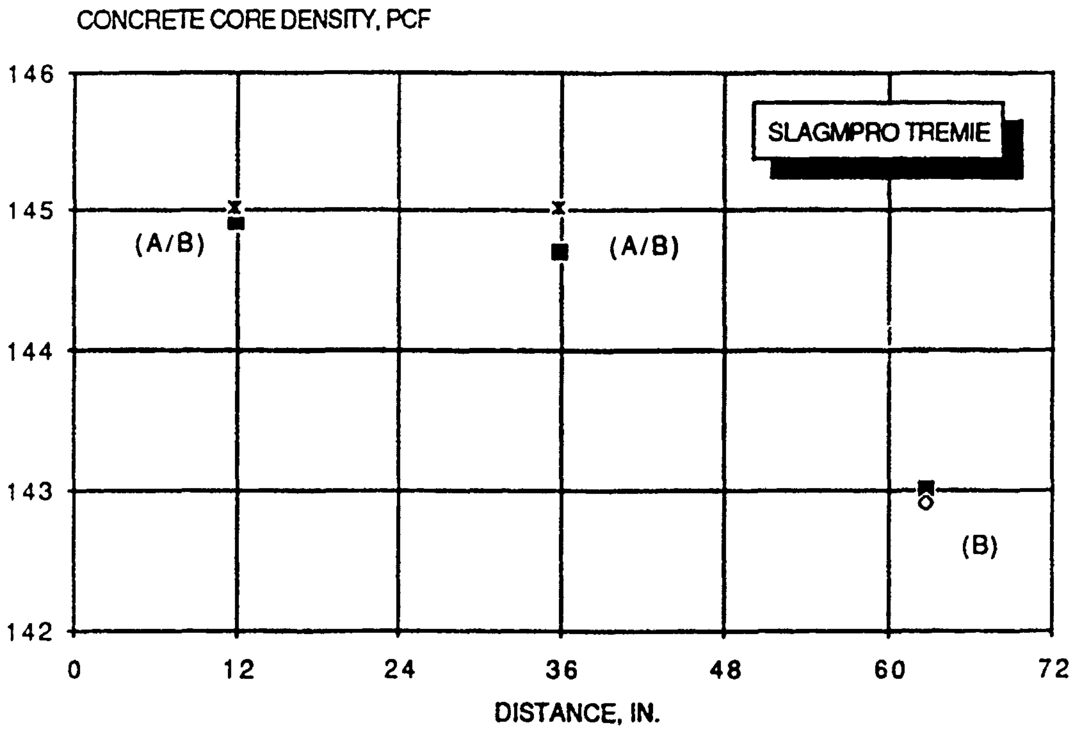
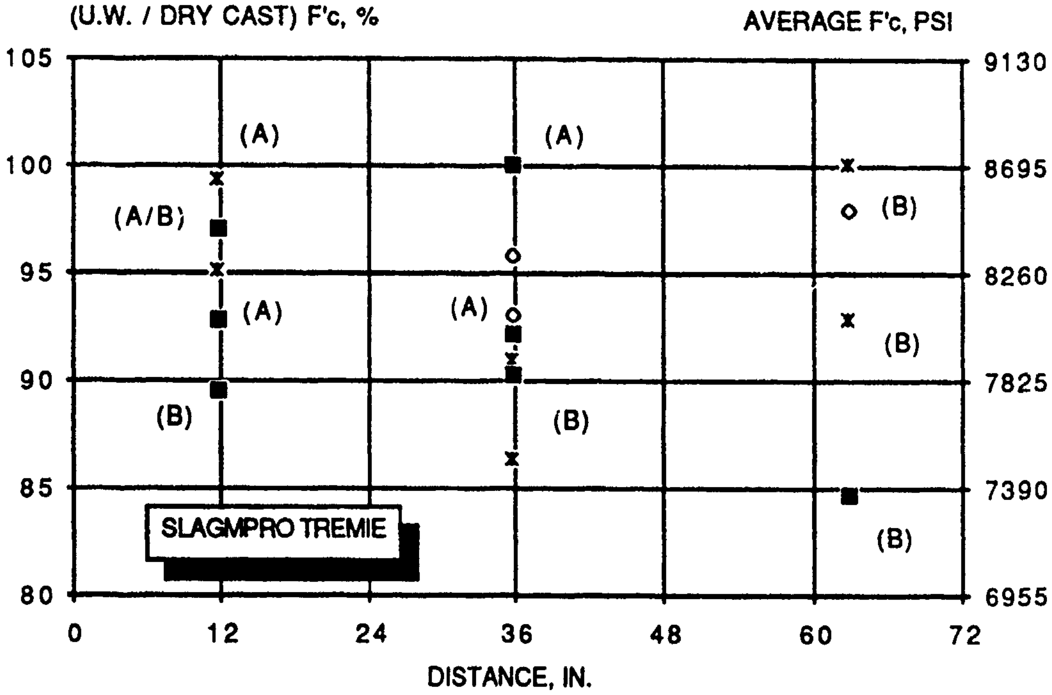


Fig. 58--Unit Weight Values along the SLAGMPRO-TREMIE Slab

Table 21. Density Test Results of the SLAGMPRO-TREMIE Cores

MIX METHOD	SLAGMPRO TREMIE						
CUT CORE DESCRIPTIONS	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	DENSITY CUT CORE, PCF	% DENSITY INCREASE CUT/UNCUT	% OF AVG. CONTROL DENSITIES
MIX A CONTROL				99	147.9		100
MIX B CONTROL				99	147.8		100
2" A 6.1" B	9	12	TOP	99	144.9	0.07	98
2" A, 6.15" B	15	12	TOP	99	145	0.14	98.1
2.6" A, 4.4" B	5	36	TOP	99	144.7	0.35	97.9
2.8" A, 4" B	15	36	TOP	99	145	0.13	98.1
4.15" B	8	63	ACROSS	99	143	0.35	96.7
3.82" B	26	63	ACROSS	99	142.9	0.28	96.7



MIXTURE METHOD	SLAGMPRO TREMIE							
CAPPED CORE DESCRIPTIONS	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	L/D	ADJ. FACTOR	F'c, PSI	% CONT. A OR B F'c
MIX A CONTROL				100			8870	100
MIX B CONTROL				100			8520	100
2.12" A, 2.2" B	9	12	TOP	100	1.548	0.964	8435	97
4.32" B	9	12	MIDDLE	100	1.548	0.964	7615	89.4
2.86" A	15	12	BOTTOM	100	1.025	0.876	8795	99.2
3.3" A	9	12	MIDDLE	100	1.183	0.914	8415	94.9
2.79" A	9	12	MIDDLE	100	1	0.87	8225	92.7
4.89" A	8	36	BOTTOM	100	1.753	0.979	8175	92.1
2.53" A	22	36	BOTTOM	100	1	0.87	8485	95.7
2.96" A	22	36	BOTTOM	100	1.06	0.884	8245	93
2.79" A	15	36	TOP	100	1	0.87	8055	90.8
3.78" B	15	36	MIDDLE	100	1.355	0.943	7340	86.2
2.79" A	5	36	TOP	100	1	0.87	8890	100
3.68" B	5	36	MIDDLE	100	1.319	0.938	7690	90.2
4.14" B	26	63	ACROSS	100	1.484	0.958	8335	97.8
4.47" B	8	63	ACROSS	100	1.602	0.968	7205	84.6
4.36" B	15	63	ACROSS	100	1.563	0.965	8540	100
4.13" B	18	63	ACROSS	100	1.48	0.958	7895	92.7

Fig. 59, Table 22. Compressive Strength Values along the SLAGMPRO-TREMIE Slab

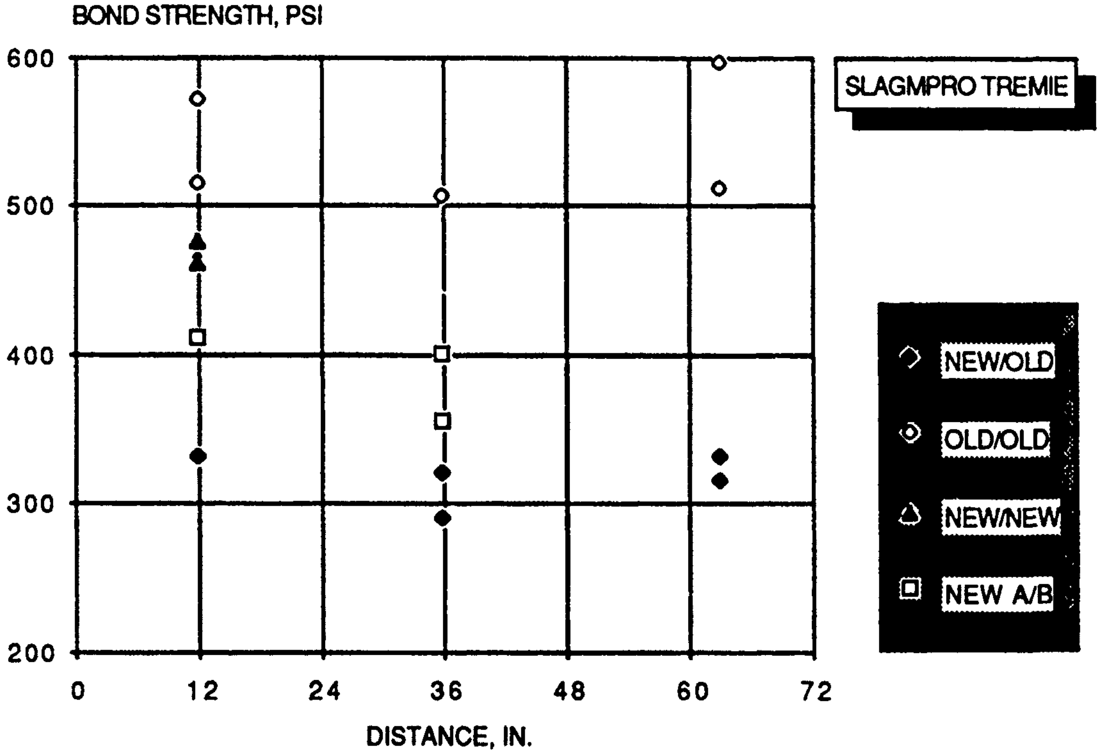


Fig. 60--Bond Strength Values along the SLAGMPRO-TREMIE Slab

Table 23. Bond Strength Values of the SLAGMPRO-TREMIE Slab

MIX METHOD		SLAGMPRO TREMIE			AGE:	100 DAYS
CUT CORE DESCRIPTIONS	BONDED MAT'S	COORDINATES X, IN.	COORDINATES Y, IN.	BOND STRENGTH, PSI	% OF MIX	COMMENTS
5.1" OLD, 6.6" A	A / OLD	9	12	330	64 OLD, 72 A	@ BOND, FLAT
5" OLD, 5.1" A	A / OLD	8	36	320	63 OLD	1/2 BOND, 1/2 A
5.2" OLD, 6.1" A	A / OLD	22	36	290	----	1/2 A, 1/2 OLD
4.4" OLD, 5.1" B	B / OLD	15	63	330	65 OLD	@ BOND, FLAT
5" OLD, 4" B	B / OLD	18	63	315	53 OLD	@ BOND, FLAT
5" OLD	OLD/OLD	15	12	570	----	JAGGED, ANGULAR
5.1" OLD	OLD/OLD	9	12	515	----	JAGGED, ANGULAR
5" OLD	OLD/OLD	8	36	505	----	JAGGED, ANGULAR
4.4" OLD	OLD/OLD	15	63	510	----	JAGGED, ANGULAR
5" OLD	OLD/OLD	18	63	595	----	JAGGED, ANGULAR
6.4" A	A / A	15	12	475	----	JAGGED, ANGULAR
6.6" A	A / A	9	12	460	----	JAGGED, ANGULAR
2" A, 6.2" B	A / B	15	12	410	----	20% IN A, 80% IN B
2.75" A, 5.5" B	A / B	15	36	355	----	MOSTLY IN B
2.6" A, 4.4" B	A / B	15	36	400	----	MOSTLY IN B

Fig. 61--Picture of the FAMPRO-TREMIE Slab

Fig. 62--Section III of the FAMPRO-TREMIE Slab

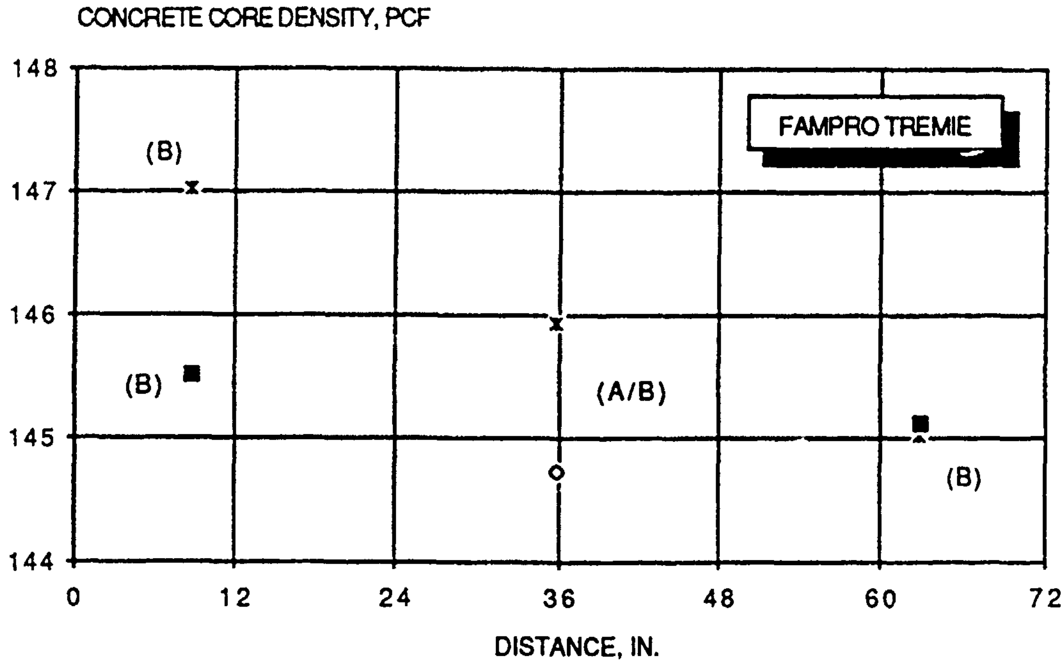


Fig. 63--Unit Weight Values along the FAMPRO-TREMIE Slab

Table 24. Density Test Results of the FAMPRO-TREMIE Cores

MIX METHOD	FAMPRO TREMIE						
CUT CORE DESCRIPTIONS	COORDINATES X IN.	Y. IN.	CORED FROM	AGE, DAYS	DENSITY CUT CORE PCF	% DENSITY INCREASE CUT/UNCUT	% OF AVG. CONTROL DENSITIES
MIX A CONTROL				103	147.5		100
MIX B CONTROL				103	148.8		100
5.77" B	4	9	TOP	103	145.5	0	98.2
7.7" B	15	9	TOP	103	147	0	99.2
4.2" A, 3.3" B	15	36	TOP	103	145.9	0.07	98.5
4.1" A, 2.55" B	26	36	TOP	103	144.7	0	97.8
3.02" B	4	63	TOP	103	145	0	98
3.17" B	12	63	TOP	103	145.1	0.07	97.9

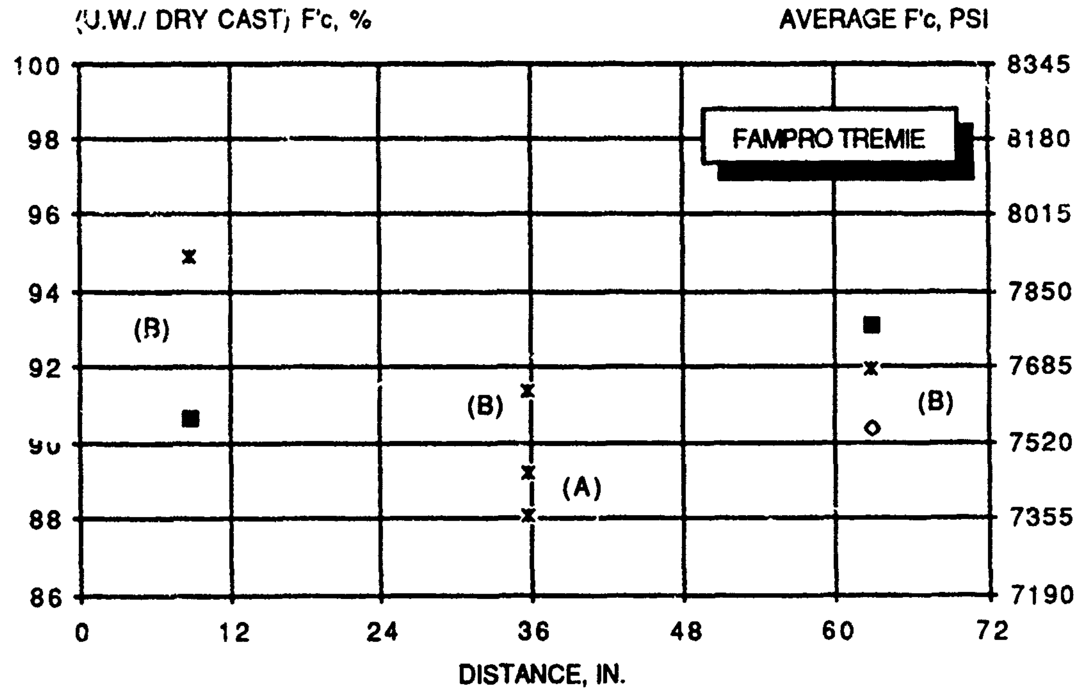


Fig. 64--Compressive Strength Values along the FAMPRO-TREMIE Slab

Table 25. Compressive Strength Results of FAMPRO-TREMIE Cores

MIXTURE METHOD	FAMPRO TREMIE							
CAPPED CORE DESCRIPTIONS	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	L/D	ADJ. FACTOR	F'c, PSI	% CONT. A OR B F'c
MIX A CONTROL				108			8395	100
MIX B CONTROL				108			8295	100
6.08" B	4	9	TOP	109	2.187	1	7515	90.6
8" B	15	9	TOP	109	2.878	1	7865	94.8
2.9" A	11	36	BOTTOM	109	1.039	0.879	7480	89.1
4.1" A	15	36	TOP	109	1.47	0.956	7385	88
3.19" B	15	36	TOP	109	1.143	0.904	7575	91.3
3.3" B	12	63	TOP	109	1.187	0.915	7625	91.9
3.46" B	4	63	TOP	109	1.245	0.929	7725	93.1
3.39" B	21	63	ACROSS	109	1.215	0.922	7490	90.3

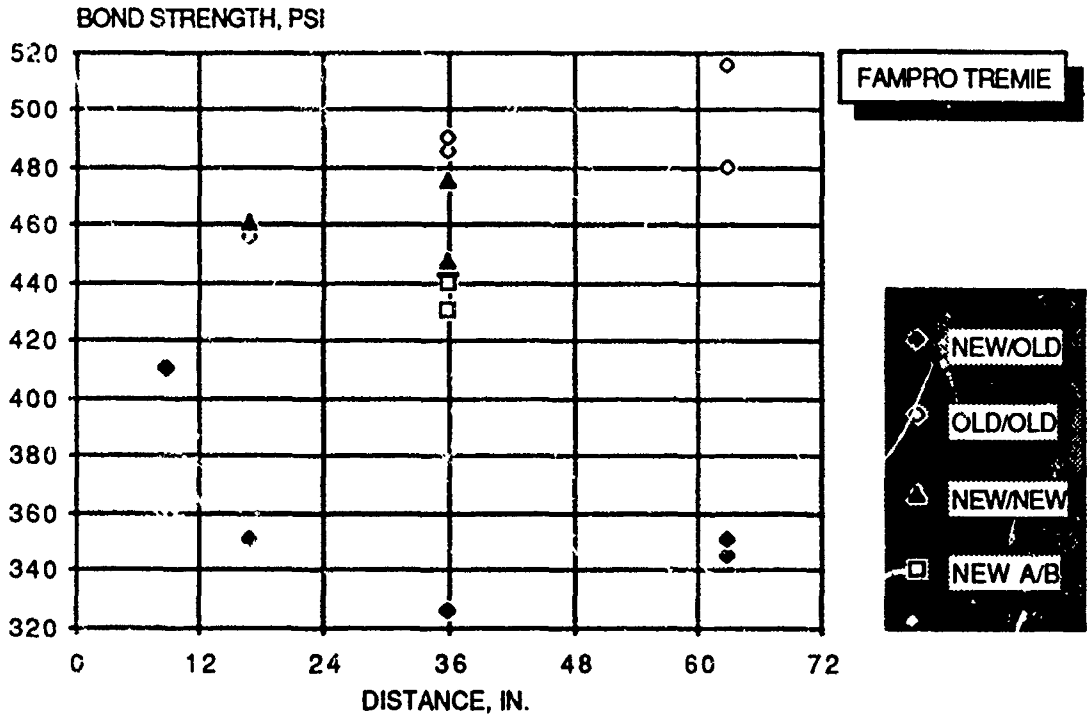


Fig. 65--Bond Strength Values along the FAMPRO-TREMIE Slab

Table 26. Bond Strength Test Results of the FAMPRO-TREMIE Cores

MIX METHOD	FAMPRO TREMIE				AGE:	109 DAYS
CUT CORE DESCRIPTIONS	BONDED MAT'S	COORDINATES X, IN.	Y, IN.	BOND STRENGTH, PSI	% OF MIX	COMMENTS
5.9" OLD, 6.1" A	A / OLD	13	9	410	----	@ BOND, FLAT
5.5" OLD, 6.25" A	A / OLD	15	17	350	77 OLD, 76 A	@ BOND, FLAT
5.25" OLD, 7" A	A / OLD	11	36	325	66 OLD, 68 A	@ BOND, FLAT
5.25" OLD, 3.75" B	B / OLD	21	63	345	72 OLD	@ BOND, FLAT
4.2" OLD, 3.6" B	B / OLD	15	63	350	68 OLD	@ BOND, FLAT
5.5" OLD	OLD/OLD	15	17	455	----	JAGGED, ANGULAR
5.25" OLD	OLD/OLD	11	36	485	----	JAGGED, ANGULAR
5.5" OLD	OLD/OLD	19	36	490	----	JAGGED, ANGULAR
5.25" OLD	OLD/OLD	21	63	480	----	JAGGED, ANGULAR
4.2" OLD	OLD/OLD	15	63	515	----	JAGGED, ANGULAR
6.25" A	A / A	15	17	460	----	JAGGED, ANGULAR
7" A	A / A	11	36	475	----	JAGGED, ANGULAR
6. A	A / A	19	36	445	----	JAGGED, ANGULAR
4.2" A, 3.3" B	A / B	15	36	440	----	@ BOND AND IN A
4.15" A, 2.55" B	A / B	26	36	430	----	@ BOND AND IN B

Fig. 66--Picture of the SLAGMPRO-INCLINED TREMIE Slab

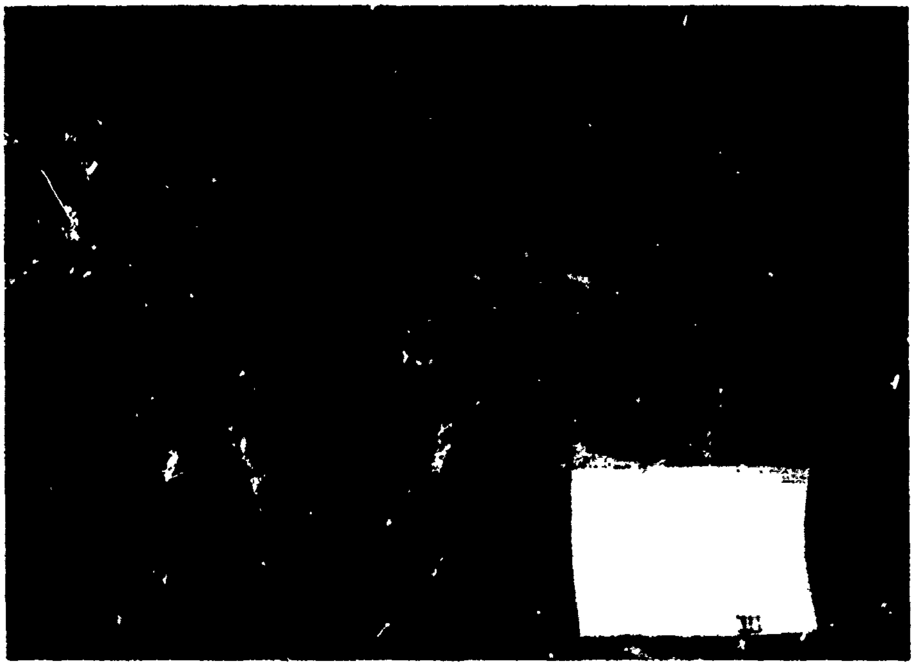


Fig. 67--Section III of the SLAGMPRO-INCLINED TREMIE Slab

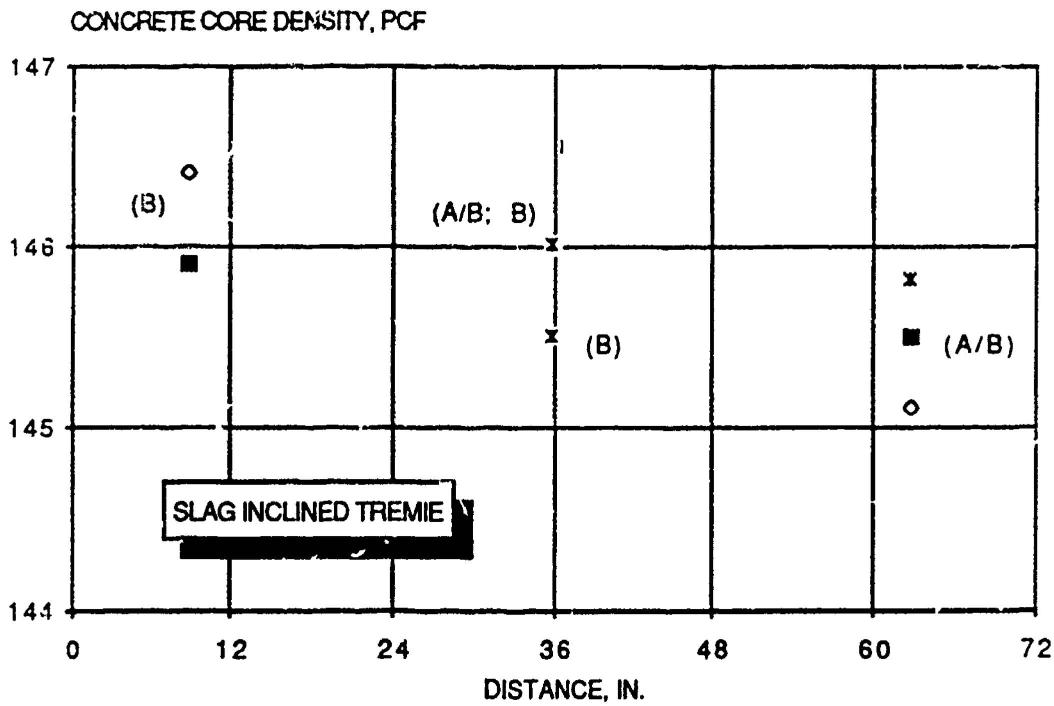


Fig. 68--Unit Weight Values along the SLAGMPRO-INCLINED TREMIE Slab

Table 27. Density Results of the SLAGMPRO-INCLINED TREMIE Cores

MIX METHOD	SLAGMPRO INCLINED TREMIE						
CUT CORE DESCRIPTION	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	DENSITY CUT CORE, PCF	% DENSITY INCREASE CUT/UNCUT	% OF AVG. CONTROL DENSITIES
MIX A CONTROL				99	148.3		100
MIX B CONTROL				99	149.1		100
7.55" B	7	9	TOP	99	145.9	0.28	98.1
7" B	21	9	TOP	99	146.4	0.21	98.4
3.3" B	15	36	TOP	99	146	0.48	98.2
2.85" B	16	36	TOP	99	145.5	0.07	97.8
4.4" A, 3.55" B	24.5	36	TOP	99	146	0.21	98.2
3.8" A, 3.6" B	4.5	63	ACROSS	99	145.5	0.28	97.8
4.6" A, 3.1" B	15	63	TOP	99	145.8	0.28	98
4" A, 2" B	25.5	63	ACROSS	99	145.1	0.14	97.6

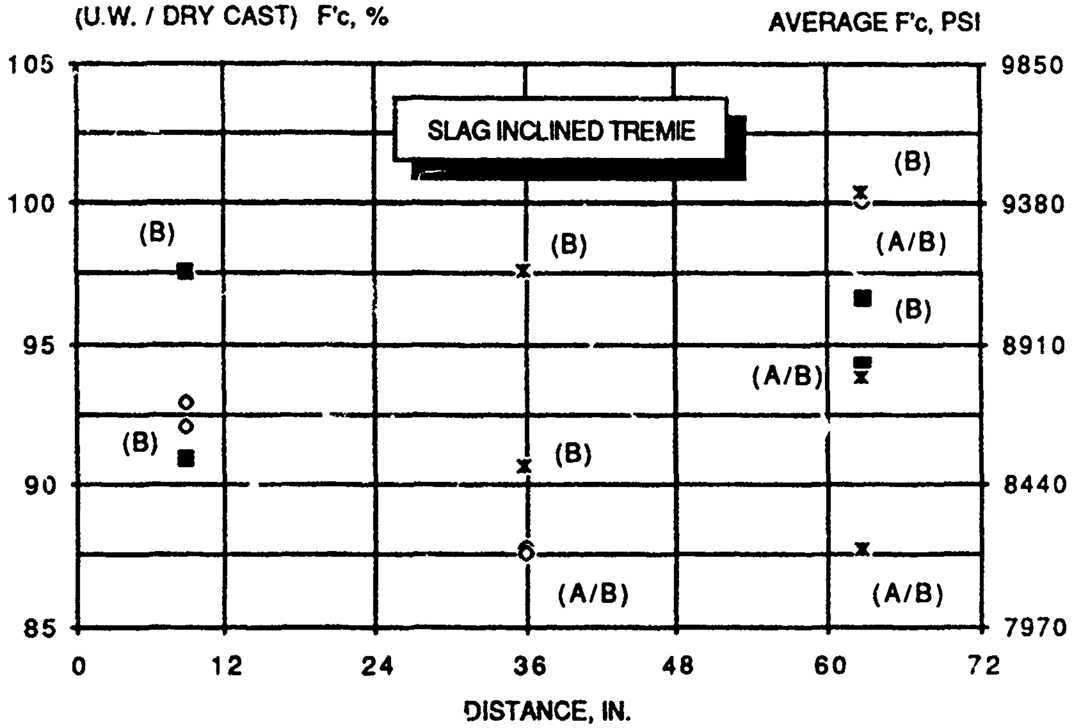
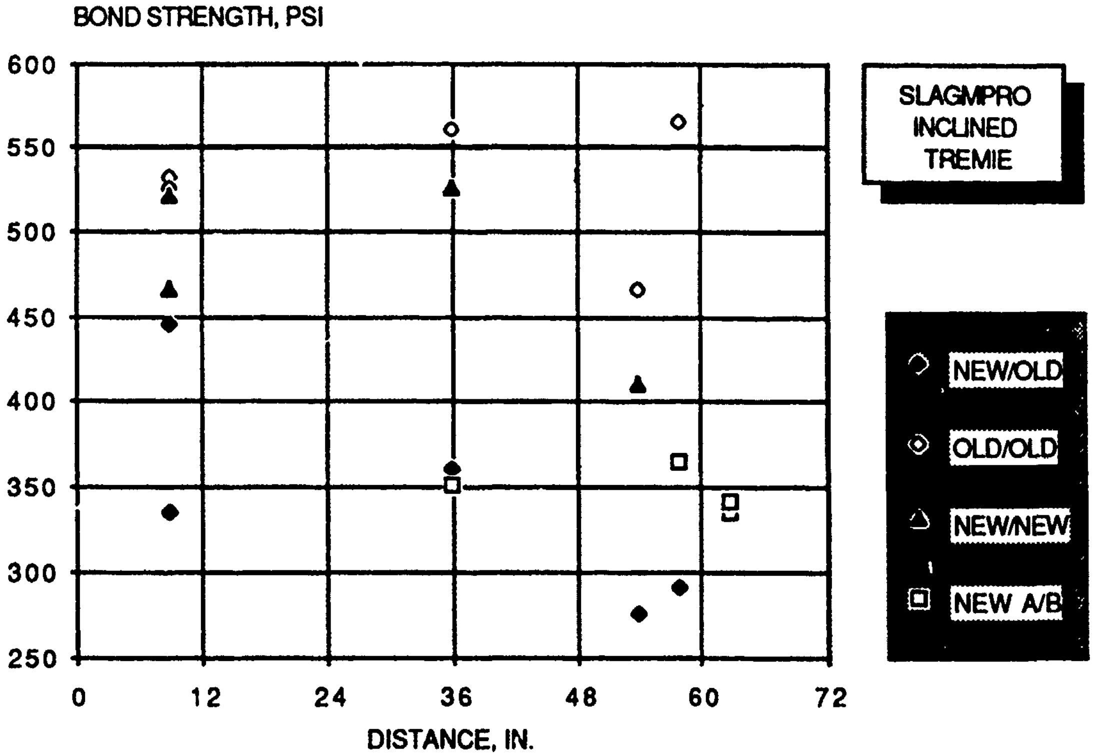


Fig. 69--Compressive Strength Values along the SLAGMPRO-INCLINED TREMIE Slab

Table 28. Compressive Strength Values of the SLAGMPRO-INCLINED TREMIE Slab

MIXTURE METHOD	SLAGMPRO INCLINED TREMIE							
CAPPED CORE DESCRIPTIONS	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	L/D	ADJ. FACTOR	F'c, PSI	% CONT. A OR B F'c
MIX A CONTROL				100			9505	100
MIX B CONTROL				100			9255	100
3.82" B	21	9	TOP	100	1.369	0.944	8605	92.9
3.75" B	21	9	TOP	100	1.344	0.941	8515	92
4.06" B	7	9	TOP	100	1.455	0.955	9025	97.5
4.29" B	7	9	TOP	100	1.538	0.963	8410	90.9
3.49" A	24.5	36	TOP	100	1.251	0.93	8335	87.7
4.5" B	24.5	36	TOP	100	1.613	0.969	8100	87.5
3.22" B	15	36	TOP	100	1.154	0.907	8380	90.6
3.68" B	15	36	TOP	100	1.319	0.938	9025	97.5
2" A, 1.29" B	25.5	63	ACROSS	100	1.179	0.913	9380	100
1.57" A, 3.1" B	15	63	TOP	100	1.674	0.974	8220	87.6
3.57" B	15	63	MIDDLE	100	1.28	0.934	9285	100.3
3.99" A	4.5	63	BOTTOM	100	1.43	0.952	8950	94.2
3.78" B	4.5	63	TOP	100	1.355	0.943	8940	96.6
1.59" A, 1.2" B	18	63	BOTTOM	100	1	0.87	8795	93.7



MIX METHOD		SLAGMPRO INCLINED TREMIE			AGE:	100 DAYS
CUT CORE DESCRIPTIONS	BONDED MAT'S	COORDINATES X, IN.	COORDINATES Y, IN.	BOND STRENGTH, PSI	% OF MIX	COMMENTS
5.4" OLD, 5.7" A	A / OLD	15	9	445	86 OLD, 86 A	@ BOND, JAGGED
5.5" OLD, 4.5" A	A / OLD	21	9	335	64 OLD, 72 A	@ BOND, JAGGED
4.75" OLD, 5.75" A	A / OLD	21	36	360	64 OLD, 69 A	PULLOUT, SOME IN A
4.65" OLD, 5.1" A	A / OLD	12	54	275	59 OLD, 67 A	@ BOND, FLAT
4.8" OLD, 6.8" A & B	A / OLD	18	58	290	51 OLD, 79 A	@ BOND
5.4" OLD	OLD/OLD	15	9	530	----	JAGGED, ANGULAR
5.5" OLD	OLD/OLD	21	9	525	----	JAGGED, ANGULAR
4.75" OLD	OLD/OLD	21	36	560	----	JAGGED, ANGULAR
4.65" OLD	OLD/OLD	12	54	465	----	JAGGED, ANGULAR
4.8" OLD	OLD/OLD	18	63	565	----	JAGGED, ANGULAR
5.7" A	A / A	15	9	520	----	
4.5" A	A / A	21	9	465	----	
5.75" A	A / A	21	36	525	----	
5.1" A	A / A	12	54	410	----	
4.4" A, 3.5" B	A / B	25	36	350	----	PULLOUTS, JAGGED
4.7" A, 2.1" B	A / B	18	63	365	----	PULLOUTS, JAGGED
3.1" A, 4.6" B	A / B	15	63	335	----	1/2 IN A, 1/2 IN B
3.8" A, 3.4" B	A / B	5	63	340	---	@ BOND, ANGULAR

Fig. 70, Table 29. Bond Strength Values of the SLAGMPRO-INCLINED TREMIE Slab

Fig. 71--Picture of the HSFLPRO-INCLINED TREMIE Slab

Fig. 72--Section IV of the HSFLPRO-INCLINED TREMIE Slab

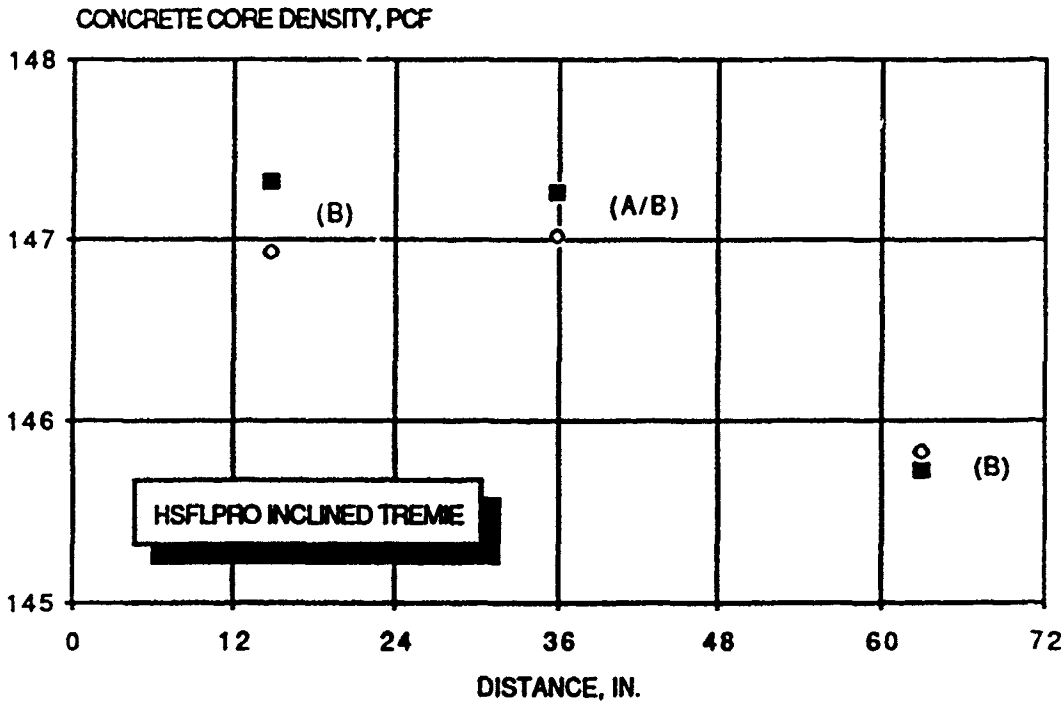


Fig. 73--Unit Weight Values along the HSFLPRO-INCLINED TREMIE Slab

Table 30. Density Results of the HSFLPRO-INCLINED TREMIE Cores

MIX METHOD	HSFLPRO INCLINED TREMIE						
CUT CORE DESCRIPTIONS	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	DENSITY CUT CORE PCF	% DENSITY INCREASE CUT/UNCUT	% OF AVG. CONTROL DENSITIES
MIX A CONTROL				100	150.1		100
MIX B CONTROL				100	150		100
6.75" B	3.5	15	TOP	100	147.3	0.2	98.2
5.8" B	23.5	15	TOP	100	146.9	0.2	97.9
4.8" A, 4.2" B	3.5	36	TOP	100	147.2	0.16	98.2
3.5" A, 4" B	26.5	36	TOP	100	147	0.24	98
4.75" B	3.5	63	TOP	100	145.7	0.27	97.1
5.15" B	26.5	63	TOP	100	145.8	0.15	97.2

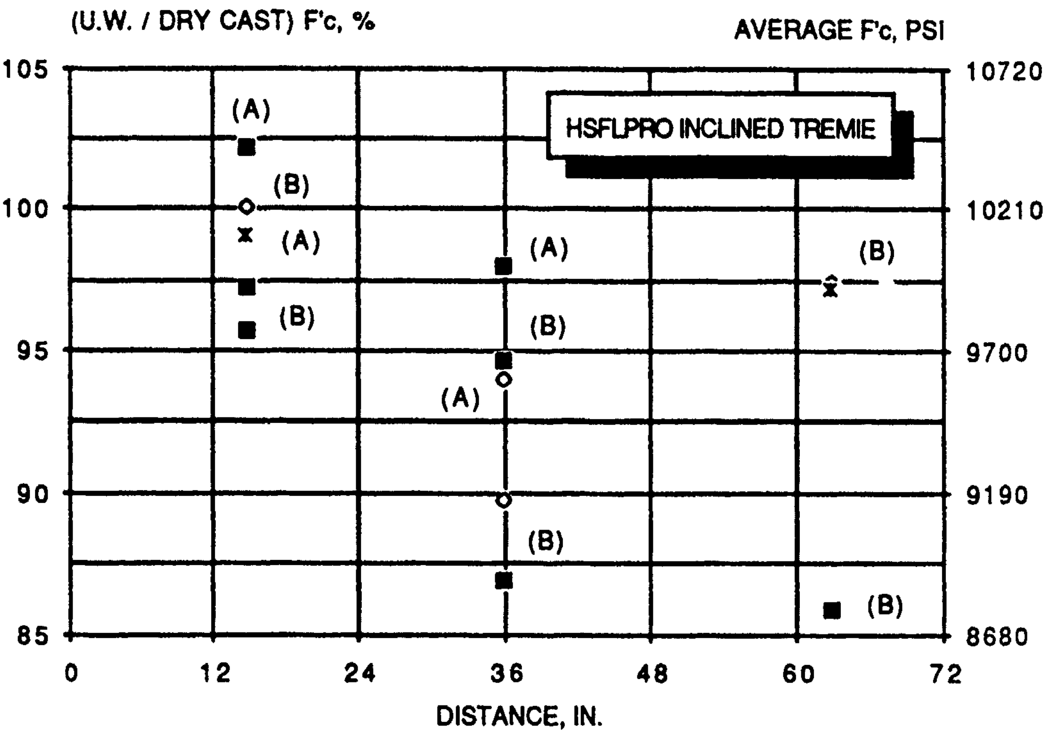


Fig. 74--Compressive Strength Values along the HSFLPRO-INCLINED TREMIE Slab

Table 31. Compressive Strength Values of the HSFLPRO-INCLINED TREMIE Slab

MIXTURE METHOD	HSFLPRO INCLINED TREMIE							
CAPPED CORE DESCRIPTIONS	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	L/D	ADJ. FACTOR	F'c, PSI	% CONT. A OR B F'c
MIX A CONTROL				101			10135	100
MIX B CONTROL				101			10280	100
3.18" B	3.5	15	TOP	102	1.14	0.903	9845	95.7
3.68" B	3.5	15	TOP	102	1.319	0.938	9990	97.2
6.08" B	23.5	15	TOP	102	2.179	1	10285	100
3.34" A	10	15	BOTTOM	102	1.197	0.917	10355	102.1
2.79" A	15	15	BOTTOM	102	1	0.87	10035	99
3.14" B	8	36	BOTTOM	102	1.125	0.9	8935	86.9
3.08" B	22	36	BOTTOM	102	1.104	0.895	9220	89.7
4.73" A	3.5	36	TOP	102	1.695	0.976	9925	97.9
3.87" B	3.5	36	TOP	102	1.387	0.946	9720	94.6
3.74" B	26.5	36	TOP	102	1.34	0.941	9665	94
5.01" B	3.5	63	TOP	102	1.796	0.984	8815	85.8
5.47" B	26.5	63	TOP	102	1.961	0.997	10010	97.4
5.13" B	15	63	TOP	102	1.839	0.987	9980	97.1

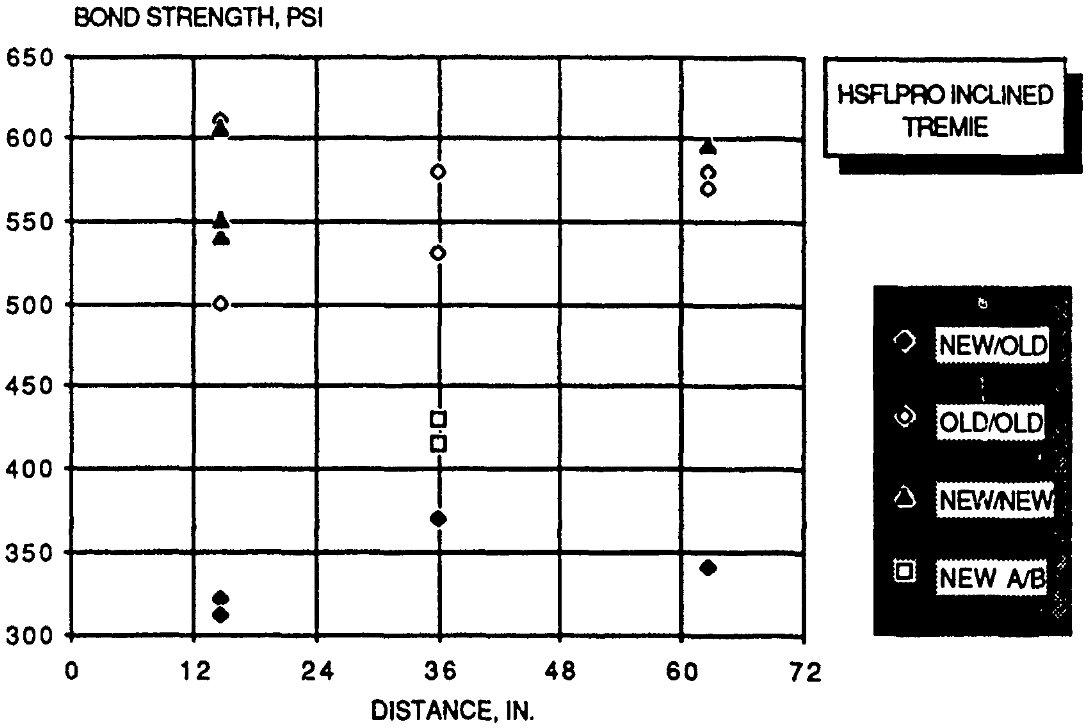


Fig. 75--Bond Strength Values of the HSFLPRO-INCLINED TREMIE Slab

Table 32. Bond Strength Values of the HSFLPRO-INCLINED TREMIE Slab

MIX METHOD		HSFLPRO INCLINED TREMIE			AGE:	100 DAYS
CUT CORE DESCRIPTIONS	BONDED MAT'S	COORDINATES X, IN.	COORDINATES Y, IN.	BOND STRENGTH, PSI	% OF MIX	COMMENTS
4.9" OLD, 6.9" A	A / OLD	10	15	320	64 OLD, 53 A	3/4 IN BOND
5" OLD, 6.6" A	A / OLD	15	15	310	51 OLD, 57 A	@ BOND, FLAT
5.2" OLD, 6.9" B	B / OLD	8	36	370	64 OLD	@ BOND, FLAT
5" OLD, 5.2" B	B / OLD	15	63	340	59 OLD	@ BOND, FLAT
4.9" OLD	OLD/OLD	10	15	500	----	JAGGED, ANGULAR
5" OLD	OLD/OLD	15	15	610	----	JAGGED, ANGULAR
5.2" OLD	OLD/OLD	8	36	580	----	JAGGED, ANGULAR
5.2" OLD	OLD/OLD	22	36	530	----	JAGGED, ANGULAR
5" OLD	OLD/OLD	15	63	580	----	JAGGED, ANGULAR
5" OLD	OLD/OLD	22	63	570	----	JAGGED, ANGULAR
6.9" A	A / A	10	15	605	----	JAGGED, ANGULAR
6.6" A	A /A	15	15	540	----	JAGGED, ANGULAR
6.75" B	B / B	4	15	550	----	JAGGED, ANGULAR
5.3" B	B / B	22	63	595	----	JAGGED, ANGULAR
3.5" A, 4" B	A / B	27	36	415	----	1/2 IN A, 1/2 IN B
4.8" A, 4.2" B	A / B	4	36	430	----	JAGGED, MOST IN A

Fig. 76--Picture of the MSFMPRO-INCLINED TREMIE Slab

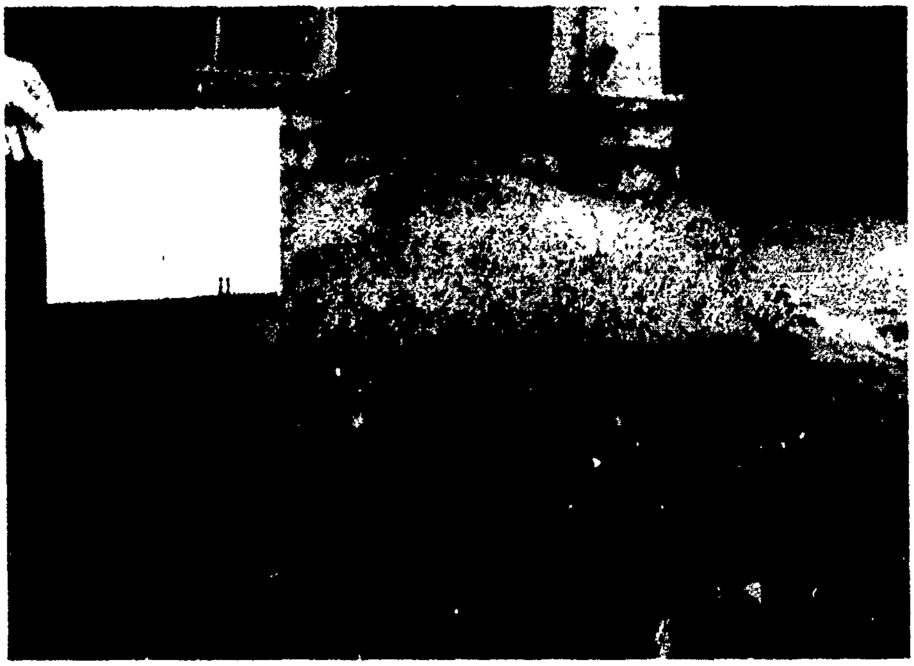


Fig. 77--Section II of the MSFMPRO-INCLINED TREMIE Slab

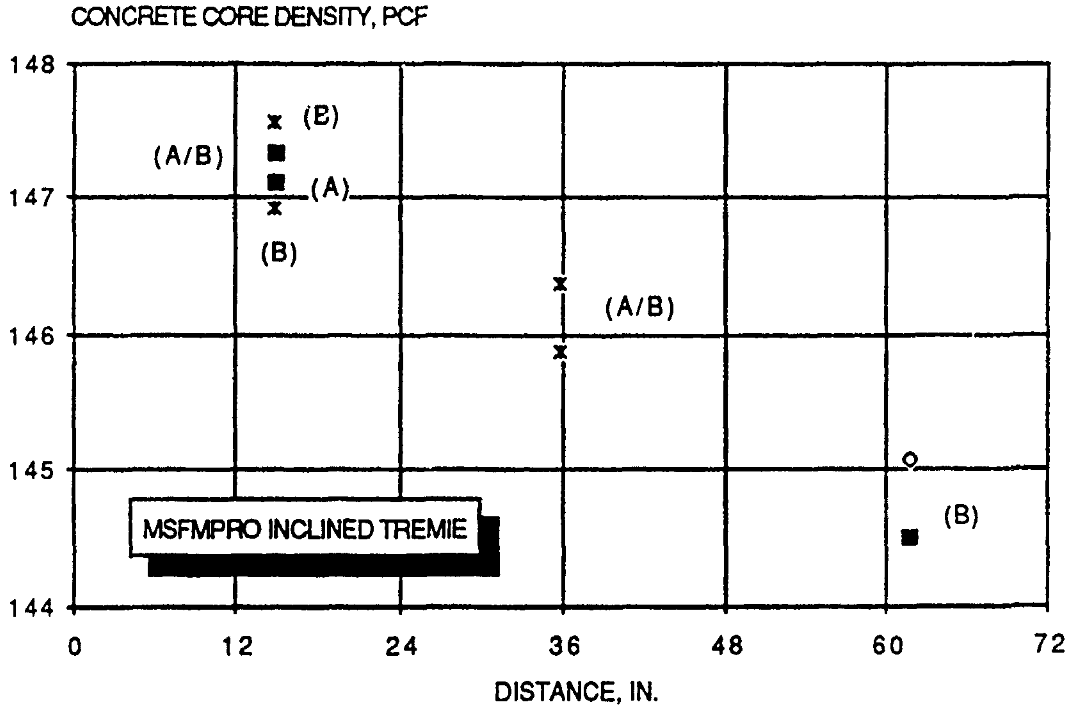
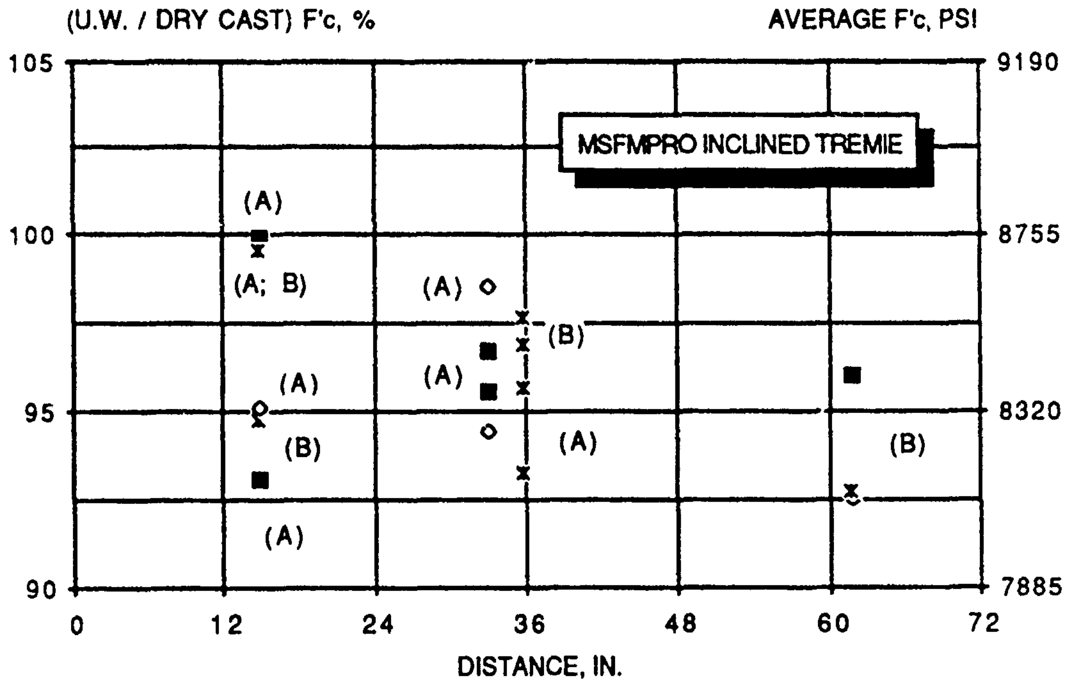


Fig. 78--Unit Weight Values along the MSFMPRO-INCLINED TREMIE Slab

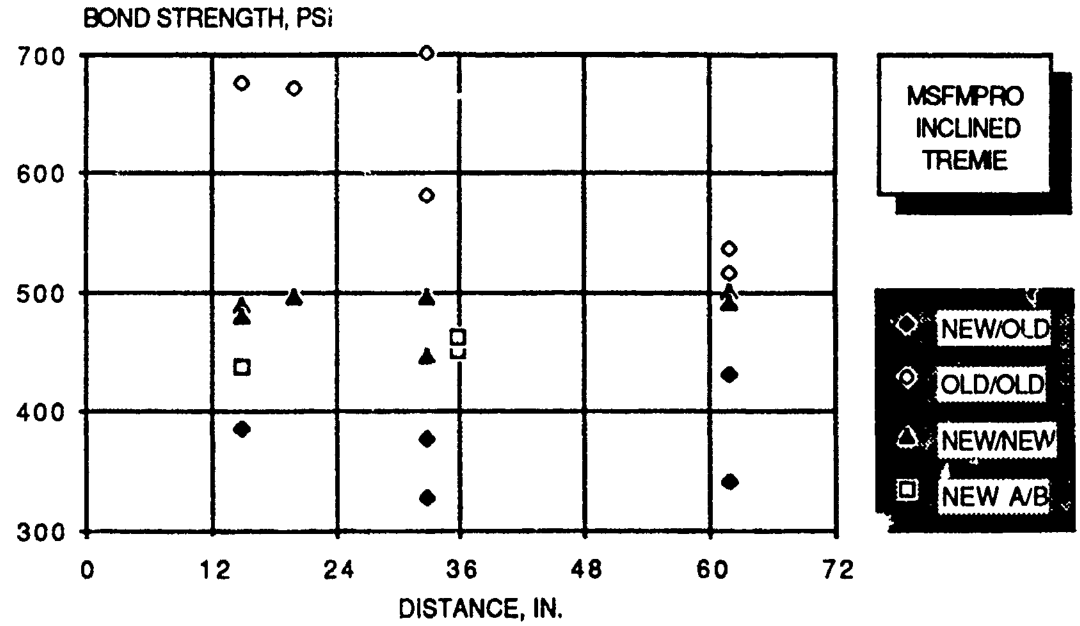
Table 33. Density Results of the MSFMPRO-INCLINED TREMIE Cores

MIX METHOD	MSFMPRO INCLINED TREMIE						
CUT CORE DESCRIPTIONS	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	DENSITY CUT CORE, PCF	% DENSITY INCREASE CUT/UNCUT	% OF AVG. CONTROL DENSITIES
MIX A CONTROL				100	148.2		100
MIX B CONTROL				100	147.9		100
4.1" A, 4.1" B	10	15	TOP	100	147.3	0.48	99.5
5.9" A	10	15	ACROSS	100	147.1	0.01	99.3
7.8" B	15	15	TOP	100	147.5	0.03	99.6
7.7" B	15	15	ACROSS	100	146.9	0.03	99.2
5.9" A, 3.7" B	15	36	TOP	100	146.3	0.07	98.8
5.4" A, 4.2" B	20	36	TOP	100	145.9	0.1	98.5
4.8" B	3.5	62	TOP	100	144.5	0.01	97.6
4.8" B	26.5	62	TOP	100	145.1	0.13	98



MIXTURE METHOD	MSFMPRO INCLINED TREMIE							
CAPPED CORE DESCRIPTIONS	COORDINATES X, IN.	Y, IN.	CORED FROM	AGE, DAYS	L/D	ADJ. FACTOR	F'c, PSI	% CONT. A OR B F'c
MIX A CONTROL				101			8720	100
MIX B CONTROL				101			8795	100
4.58" B	10	15	TOP	102	1.641	0.971	8180	93
6.28" A	10	15	MIDDLE	102	2.251	1	8685	99.6
3.58" B	15	15	TOP	102	1.283	0.933	8740	99.4
7.9" B	15	15	MIDDLE	102	2.831	1	8325	94.7
3.4" A	15	15	BOTTOM	102	1.219	0.922	8675	99.5
3.37" A	22	15	BOTTOM	102	1.208	0.92	8290	95.1
3.13" A	8	33	BOTTOM	102	1.122	0.899	8590	98.5
3.58" A	8	33	MIDDLE	102	1.283	0.934	8325	95.5
2.89" A	22	33	MIDDLE	102	1.036	0.879	8235	94.4
3.15" A	22	33	BOTTOM	102	1.129	0.901	8430	96.7
5.91" A	15	36	TOP	102	2.118	1	8130	93.2
3.27" B	15	36	MIDDLE	102	1.172	0.911	8585	97.6
5.16" A	20	36	TOP	102	1.849	0.988	8340	95.6
4.26" B	20	36	MIDDLE	102	1.527	0.962	8515	96.8
5.12" B	3.5	62	TOP	102	1.835	0.987	8135	92.5
5.13" B	3.5	62	MIDDLE	102	1.839	0.987	8445	96
5.11" B	15	62	ACROSS	102	1.831	0.987	8165	92.6

Fig. 79, Table 34. Compressive Strengths along MSFMPRO-INCLINED TREMIE Slab

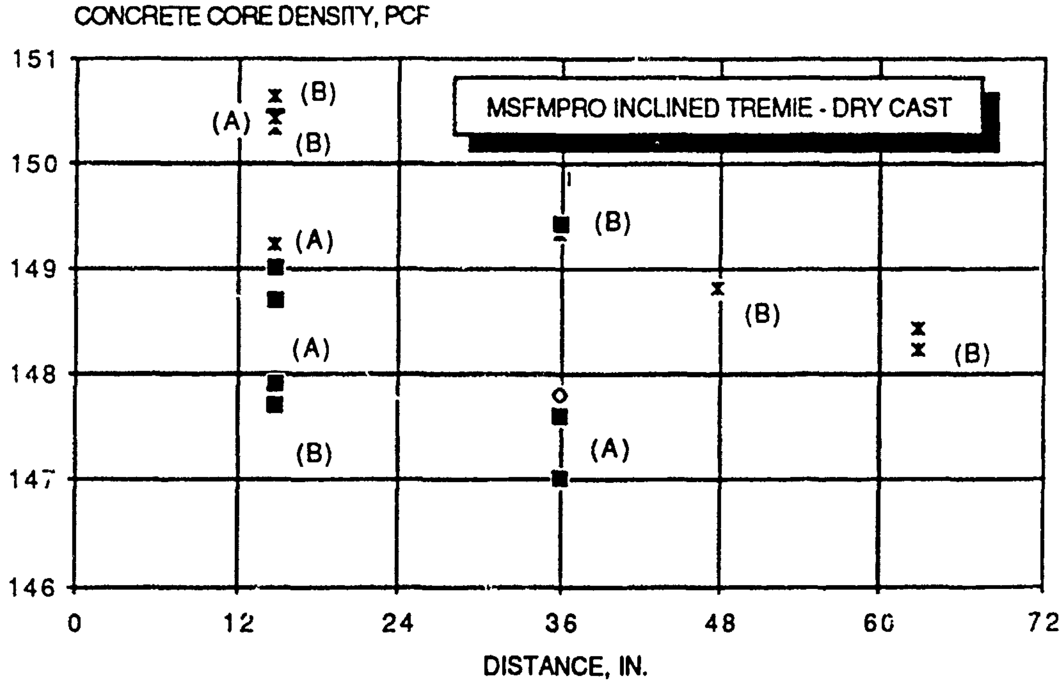


MIX METHOD		MSFMPRO INCLINED TREMIE			AGE:	100 DAYS
CUT CORE DESCRIPTIONS	BONDED MAT'S	COORDINATES X, IN.	Y, IN.	BOND STRENGTH, PSI	% OF MIX	COMMENTS
5" OLD, 6.9" A	A / OLD	15	15	385	57 OLD, 79 A	@ BOND, FLAT
4.6" OLD, 7.2" A	A / OLD	8	33	375	65 OLD, 84 A	@ BOND, FLAT
4.8" OLD, 6.5" A	A / OLD	22	33	325	46 OLD, 66 A	@ BOND
5" OLD, 5.2" B	B / OLD	15	62	340	64 OLD, 68 B	@ BOND, FLAT
5.3" OLD, 5.2" B	B / OLD	20	62	430	83 OLD, 88 B	@ BOND, FLAT
5" OLD	OLD/OLD	15	15	675	----	JAGGED, ANGULAR
5" OLD	OLD/OLD	22	20	670	----	JAGGED, ANGULAR
4.6" OLD	OLD/OLD	8	33	580	----	JAGGED, ANGULAR
4.8" OLD	OLD/OLD	22	33	700	----	JAGGED, ANGULAR
5" OLD	OLD/OLD	15	62	535	----	JAGGED, ANGULAR
5.3" OLD	OLD/OLD	20	62	515	----	JAGGED, ANGULAR
6.9" A	A / A	15	15	485	----	JAGGED, ANGULAR
7.8" B	B / B	15	15	480	----	JAGGED, ANGULAR
6.7" A	A / A	22	20	495	----	JAGGED, ANGULAR
7.2" A	A / A	8	33	445	----	JAGGED, ANGULAR
6.5" A	A / A	22	33	495	----	JAGGED, ANGULAR
5.2" B	B / B	15	62	500	----	JAGGED, ANGULAR
5.2" B	B / B	20	62	490	----	JAGGED, ANGULAR
4.1" A, 4.1" B	A / B	10	15	435	----	MOSTLY IN A
5.9" A, 3.7" B	A / B	15	36	450	----	MOSTLY IN B
5.4" A, 4.2" B	A / B	20	36	460	----	1/2 IN A, 1/2 IN B

Fig. 80, Table 35. Bond Strength Results of the MSFMPRO-INCLINED TREMIE Cores

Fig. 81--Picture of the MSFMPRO-INCLINED TREMIE DRY-CAST Slab

Fig. 82--Section II of the MSFMPRO-INCLINED TREMIE DRY-CAST Slab



MIX METHOD	MSFMPRO INCLINED TREMIE - DRY CAST						
CUT CORE DESCRIPTIONS	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	DENSITY CUT CORE, PCF	% DENSITY INCREASE CUT/UNCUT	% OF AVG. CONTROL DENSITIES
MIX A CONTROL				99	149.5		100
MIX B CONTROL				99	150		100
4.5" B	5	15	TOP	100	147.7	0.2	98.6
2.9" A	5	15	TOP	100	147.9	0.2	98.8
2.5" A	5	15	TOP	100	148.9	0.13	99.4
5.1" A	11	15	BOTTOM	100	149	0.07	99.5
2.4" B	15	15	TOP	100	150.6	0	100.6
2.5" B	15	15	TOP	100	150.3	0.4	100.4
2.2" A	15	15	TOP	100	150.4	0.07	100.4
1.9" A	15	15	TOP	100	149.3	0.4	99.7
5.9" A	19	15	BOTTOM	100	149.3	0.07	99.7
4.4" A	4	36	TOP	100	147	0.14	98.2
3.4" B	4	36	TOP	100	149.4	0.13	99.8
4.5" A	9	36	BOTTOM	100	147.6	0.2	98.6
3.2" B	15	36	TOP	100	149.3	0.27	99.7
5.9" A	21	36	BOTTOM	100	147.8	0	98.7
4" B	15	48	TOP	100	148.8	0.13	99.4
4.25" B	20	48	TOP	100	148.8	0.07	99.4
5" B	14	63	TOP	100	148.2	0	99
5.3" B	20	63	TOP	100	148.4	0.07	99.1

Fig. 83, Table 36. Densities along MSFMPRO-INCLINED TREMIE DRY-CAST Slab

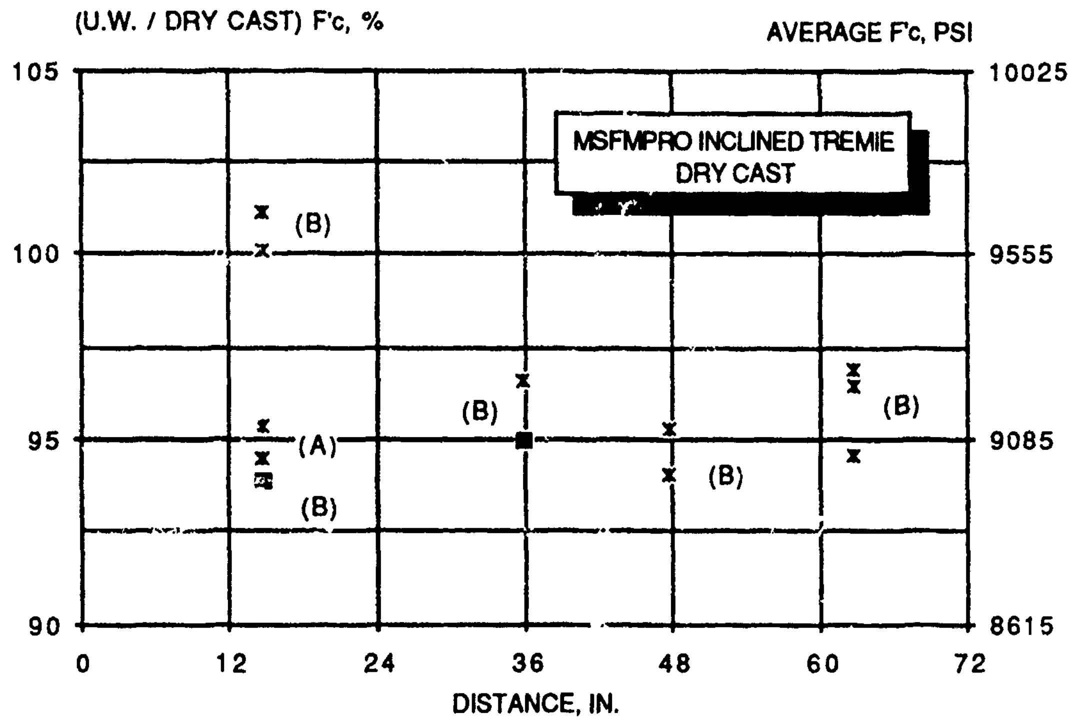
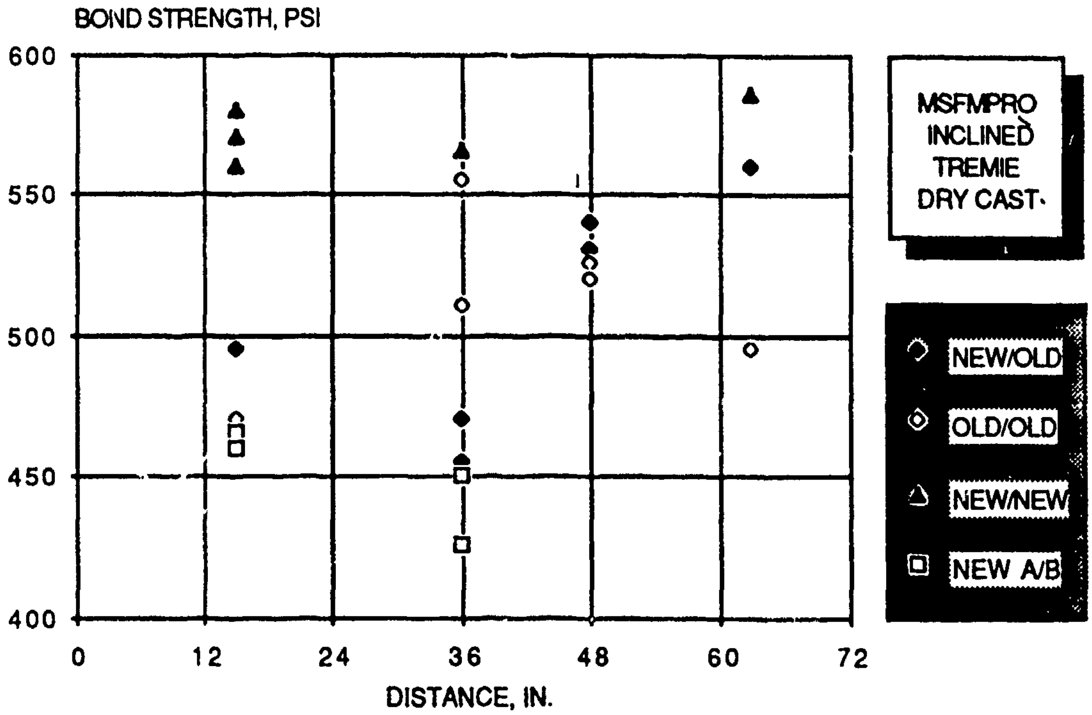


Fig. 84--Compressive Strengths of MSFMPRO-INCLINED TREMIE DRY-CAST Slab

Table 37. Compressive Strengths of MSFMPRO-INCLINED TREMIE DRY-CAST Slab

MIXTURE METHOD	MSFMPRO INCLINED TREMIE - DRY CAST							
CAPPED CORE DESCRIPTIONS	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	L/D	ADJ. FACTOR	F'c, PSI	% CONT. A OR B F'c
MIX A CONTROL				101			9515	100
MIX B CONTROL				101			9590	100
4.8" B	5	15	TOP	102	1.728	0.978	8995	93.8
2.75" B	10	15	TOP	102	1	0.87	9690	101
2.75" B	15	15	TOP	102	1	0.87	9590	100
3.25" A	19	15	BOTTOM	102	1.197	0.917	8985	94.4
2.95" A	19	15	BOTTOM	102	1.082	0.89	9070	95.3
3.52" B	4	36	TOP	102	1.29	0.935	9100	94.9
3.4" B	15	36	TOP	102	1.262	0.931	9255	96.5
4.12" B	15	48	TOP	102	1.514	0.961	9010	94
4.35" B	20	48	TOP	102	1.606	0.969	9130	95.2
2.75" B	15	63	TOP	102	1	0.87	9065	94.5
2.88" B	15	63	TOP	102	1.068	0.886	9280	96.8
5.53" B	20	63	TOP	102	2.032	1	9240	96.4



MSFMPRO	INCLINED TREMIE - DRY CAST				AGE:	100 DAYS
CUT CORE DESCRIPTIONS	BONDED MAT'S	COORDINATES X, IN.	Y, IN.	BOND STR. PSI	% OF MIX	COMMENTS
4.75" OLD, 7" A	A / OLD	19	15	495	105 OLD, 85 A	@ BOND, JAGGED
5" OLD, 6.5" A & B	A / OLD	21	36	455	89 OLD	@ BOND, FLAT
5" OLD, 5" B	B / OLD	9	36	470	85 OLD	@ BOND, FLAT
5" OLD, 4.5" B	B / OLD	15	48	540	103 OLD	1/2 IN A, 1/2 IN B
5" OLD, 4.5" B	B / OLD	20	48	530	102 OLD	1/2 IN A, 1/2 IN B
4.75" OLD, 5.75" B	B / OLD	15	63	495	100 OLD, 85 B	@ BOND MOSTLY IN B
4.75" OLD, 5.75" B	B / OLD	20	63	560	----	@ BOND MOSTLY IN B
4.75" OLD	OLD/OLD	19	15	470	----	JAGGED, ANGULAR
5" OLD	OLD/OLD	9	36	555	----	JAGGED, ANGULAR
5" OLD	OLD/OLD	21	36	510	----	JAGGED, ANGULAR
5" OLD	OLD/OLD	15	48	525	----	JAGGED, ANGULAR
5" OLD	OLD/OLD	20	48	520	----	JAGGED, ANGULAR
4.75" OLD	OLD/OLD	15	63	495	----	JAGGED, ANGULAR
6.75" A	A / A	5	15	560	----	JAGGED, ANGULAR
7" A	A / A	19	15	580	----	JAGGED, ANGULAR
4.5" A	A / A	15	36	565	----	JAGGED, ANGULAR
5.5" B	B / B	15	15	570	----	JAGGED, ANGULAR
5.75" B	B / B	15	63	585	----	JAGGED, ANGULAR
6.75" A, 5.25" B	A / B	5	15	465	83 A	MOSTLY IN B
5.5" A, 5.5" B	A / B	15	15	460	81 B	MOSTLY IN A
4.5" A, 4" B	A / B	15	36	450	80 A	@ BOND, ANGULAR
5.25" A, 4" B	A / B	4	36	425	75 A	BROKE IN A

Fig. 85, Table 38. Bond Strength Values along MSFMPRO-I.T. DRY-CAST Slab

Tables 39, 40. Density and Compressive Strength Results along KELCO Repair Slab

CORE NO.	COORDINATES X	Y. FT.	DESCRIPTION	AGE, DAYS	UNCUT	CUT	% INCREASE CUT/UNCUT	% CONT. DENSITIES
CONTROL			(NOT MUCH AIR)	22	145.5			100.0
A TOP	2" L	2.5	12", SEG.	22	136.7	137.2	0.40	94.3
A BOT			AIR VOIDS	22		136.3	-0.28	93.7
B TOP	2" R	2.5	11", FEW VOIDS	22	139.7	138.2	-1.08	95.0
B BOT				22		141.1	0.97	97.0
C TOP	6" R	5	12"	22	143.4	144.0	0.39	99.0
C BOT				22		143.8	0.27	98.8
D TOP	6" L	5	12"	22	143.7	144.2	0.37	99.1
D BOT				22		144.1	0.29	99.1
E TOP	1.5" L	7.5	12"	22	143.5	143.9	0.27	98.9
E BOT				22		143.8	0.20	98.8
F TOP	1.5" R	7.5	12"	22	143.5	143.8	0.24	98.8
F BOT				22		143.7	0.20	98.8
G TOP	3" L	9.5	12"	22	143.1	143.7	0.45	98.8
G BOT				22		143.8	0.55	98.9
H TOP	3" R	9.5		22	143.4	143.8	0.22	98.8
H BOT				22		143.6	0.15	98.7
I TOP	0	12	9"	22	141.7	143.8	1.49	98.8
I BOT				22		143.9	1.57	98.9
K TOP	12" L	14	9"	22	142.5	143.5	0.76	98.7
K BOT				22		144.7	1.59	99.5
L	6" L	14	8", HIT MUD	22	140.5	144.5	2.84	99.3

CORE NO.	X	Y. FT.	DAYS	IN.	L/D	ADJ. F.	F'c, PSI	F'c, CONT.
5 CONT'S			28				7280	100.0
A BOT			28	5.23	1.761	0.981	6175	84.8
B TOP	2" R	2.5	28	4.84	1.630	0.970	6220	85.4
B BOT			28	4.98	1.677	0.974	6385	87.7
C TOP	6" R	5	28	5.23	1.761	0.981	6175	84.8
C BOT			28	5.41	1.822	0.986	6885	94.6
D TOP	6" L	5	28	4.87	1.640	0.971	6895	94.7
D BOT			28	5.01	1.687	0.975	6395	87.8
E TOP	1.5" L	7.5	28	5.01	1.687	0.975	6815	93.6
E BOT			28	5.03	1.694	0.975	6250	85.9
F TOP	1.5" R	7.5	28	5.49	1.848	0.988	6690	91.9
F BOT			28	5.32	1.791	0.983	6160	84.6
G TOP	3" L	9.5	28	5.12	1.724	0.978	6350	87.2
G BOT			28	5.32	1.791	0.983	6020	82.7
H TOP	3" R	9.5	28	5.14	1.731	0.978	6470	88.9
H BOT			28	4.99	1.680	0.974	5980	82.1
I TOP	0	12	28	4.41	1.485	0.958	6305	86.6
I BOT			28	4.11	1.384	0.946	5925	81.4
K TOP	12" L	14	28	3.85	1.296	0.936	5930	81.5
K BOT			28	3.68	1.239	0.927	6815	93.6
L	6" L	14	28	4.44	1.495	0.959	6655	91.4

Appendix E - Repair of Reinforced Slabs and Deep Scour Holes

Fig. 86--Photograph of the KT-1 Placement Box

Fig. 87--Photograph of the KT-1 Concrete Placement

Fig. 88--Picture of the Final KT-1 Beam

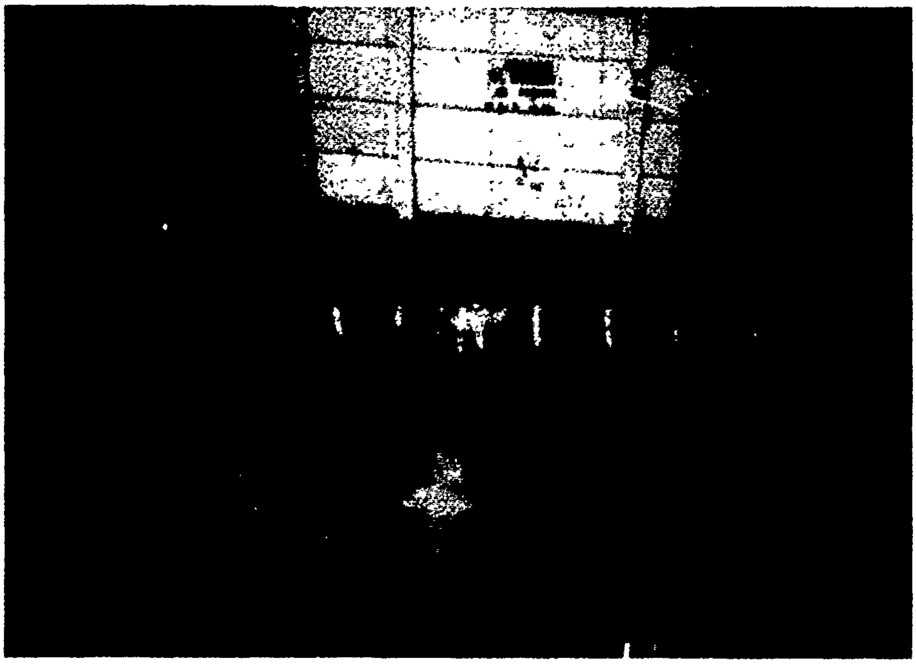


Fig. 89--Picture of the Final KT-2 Beam

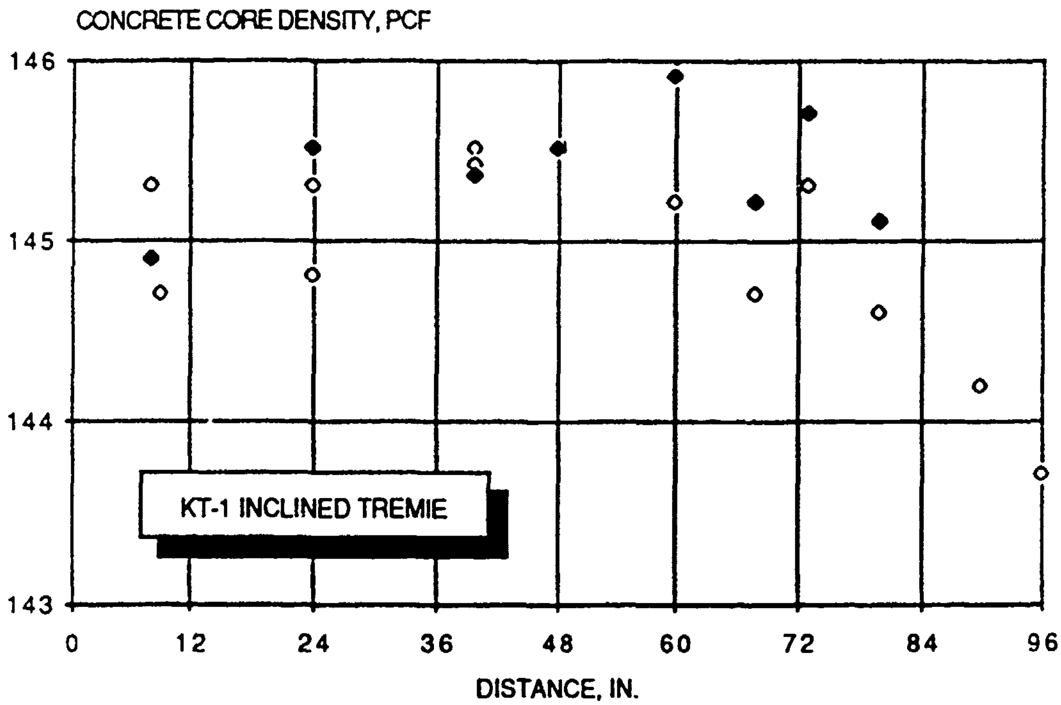


Fig. 90--Unit Weight Values along the KT-1 Beam

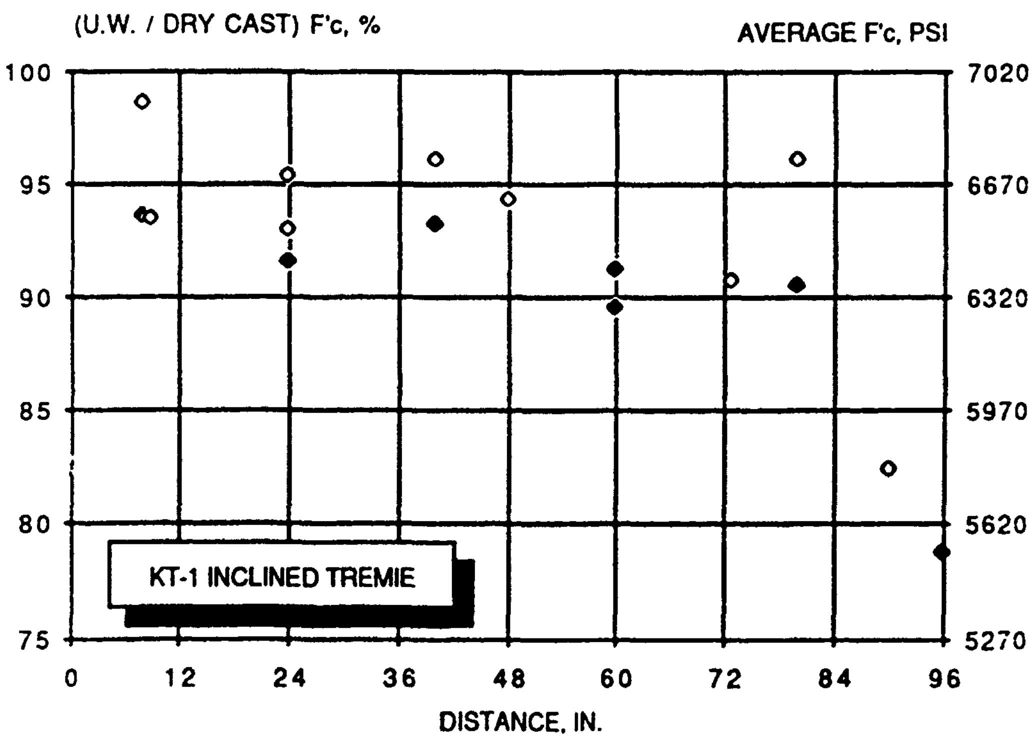


Fig. 91--Compressive Strength Values along the KT-1 Beam

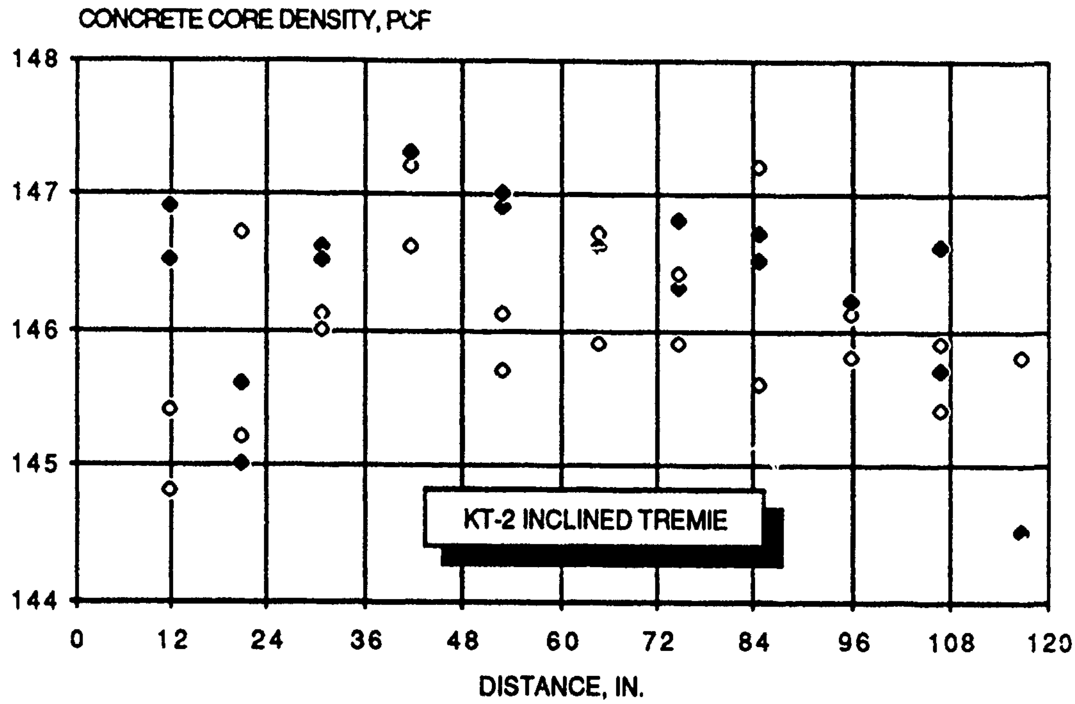


Fig. 92--Unit Weight Values along the KT-2 Beam

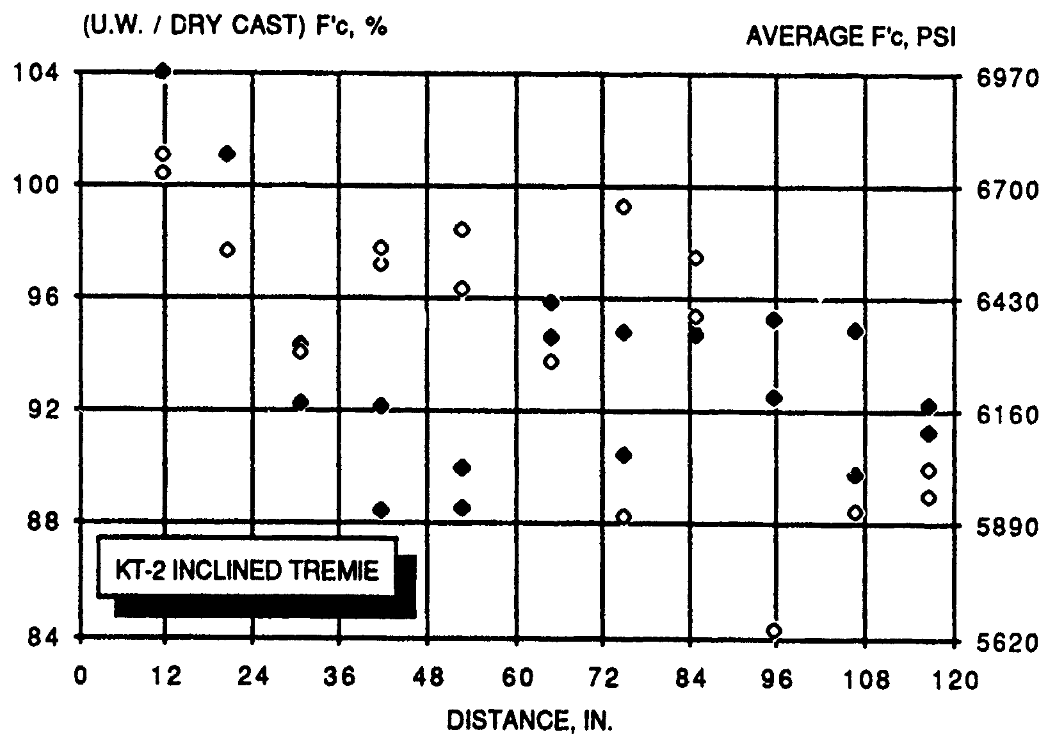


Fig. 93--Compressive Strength Values along the KT-2 Beam

Table 41. Density Results along the KT-2 Beam

MIX	KT-2		INCLINED TREMIE					
CUT CORE NO.	COORDINATES X, IN.	COORDINATES Y, IN.	CORE LENGTH, IN.	AGE, DAYS	LAITANCE RANGE, IN!	DENSITY CUT CORE, PCF	% DENSITY INCREASE CUT/UNCUT	% OF AVG. CONTROL DENSITIES
CONTROL				23		146.5		100
1 TOP	15	12	5.5	23	0	145.4	0.0	99.2
1 MIDDLE	15	12	5.25	23		146.5	0.8	100.0
2 TOP	9	12	4.75	23	0	144.8	0.0	98.8
2 MIDDLE	9	12	4.25	23		146.9	0.0	100.3
3 TOP	15	21	6	23	0	146.7	0.0	100.1
3 MIDDLE	15	21	4.5	23		145.6	0.0	99.4
4 TOP	9	21	5.6	23	0	145.2	0.7	99.1
4 MIDDLE	9	21	5.3	23		145	0.0	99.0
5 TOP	15	31	6.6	23	0	146.1	0.2	99.7
5 MIDDLE	15	31	4.25	23		146.6	0.5	100.1
6 TOP	9	31	5.6	23	0	146	0.1	99.7
6 MIDDLE	9	31	5.3	23		146.5	0.4	100.0
7 TOP	15	42	3.9	23	0	146.6	0.2	100.1
7 MIDDLE	15	42	6.3	23		146.6	0.2	100.1
8 TOP	9	42	5.2	23	0	147.2	0.5	100.5
8 MIDDLE	9	42	4.75	23		147.3	0.5	100.5
9 TOP	15	53	4.6	23	0 - 0.05	145.7	0.1	99.5
9 MIDDLE	15	53	4.5	23		146.9	0.9	100.3
10 TOP	9	53	5.5	23	0.08	146.1	0	99.7
10 MIDDLE	9	53	4.75	23		147	0.6	100.3
11 TOP	15	65	5.25	23	0.08	146.7	0.6	100.1
11 MIDDLE	15	65	5.1	23		146.6	0.5	100.1
12 TOP	9	65	5.25	23	0.08	145.9	0.3	99.6
12 MIDDLE	9	65	5	23		146.6	0.8	100.1
13 TOP	15	75	5.5	23	0.02 - 0.1	145.9	0.3	99.6
13 MIDDLE	15	75	4.8	23		146.3	0.6	99.9
14 TOP	9	75	5.25	23	0.03 - 0.1	146.4	0.4	99.9
14 MIDDLE	9	75	5.1	23		146.8	0.6	100.2
15 TOP	15	85	5.25	23	0.05 - 0.1	145.6	1.9	99.4
15 MIDDLE	15	85	5.25	23		146.5	2.5	100.0
16 TOP	9	85	6.25	23	0.05 - 0.1	147.2	2.9	100.5
16 MIDDLE	9	85	4.75	23		146.7	2.5	100.1
17 TOP	15	96	5.4	23	0.05 - 0.2	145.8	0.8	99.5
17 MIDDLE	15	96	4.8	23		146.2	1.1	99.8
18 TOP	9	96	5.25	23	0.05 - 0.2	146.1	0.8	99.7
18 MIDDLE	9	96	5.3	23		146.2	0.9	99.8
19 TOP	15	107	5.5	23	0.15 - 0.4	145.4	1	99.2
19 MIDDLE	15	107	4.9	23		145.7	1.2	99.5
20 TOP	9	107	3.75	23	0.1 - 0.5	145.9	0.9	99.6
20 MIDDLE	9	107	4.8	23		146.6	1.4	100.1
21 TOP	15	117	5.3	23	0.1 - 0.5	145.8	2	99.5
21 MIDDLE	15	117	4.25	23	& 0.3 SEG.	144.5	1.1	98.6

Table 42. Compressive Strength Values along the KT-2 Beam

MIXTURE	KT-2		INCLINED TREMIE					
CORE DESCRIPTIONS	COORDINATES X, IN.	COORDINATES Y, IN.	CORED FROM	AGE, DAYS	L/D	ADJ. FACTOR	F'c, PSI	% CONT. F'c
CONTROL				24			6700	100
5.73"	15	12	TOP	24	1.929	0.994	6960	103.9
4.48"	15	12	MIDDLE	24	1.508	0.961	6795	101.4
5.1"	9	12	TOP	24	1.717	0.977	6770	101.0
4.49"	9	12	MIDDLE	24	1.512	0.961	6965	104.0
6.13"	15	21	TOP	24	2.064	1	6770	101.0
5.97"	9	21	TOP	24	2.010	1	6540	97.6
6.88"	15	31	TOP	24	2.317	1	6320	94.3
4.4"	15	31	MIDDLE	24	1.481	0.958	6180	92.2
5.9"	9	31	TOP	24	1.987	0.999	6315	94.3
5.56"	9	31	MIDDLE	24	1.872	0.99	6300	94.0
4.27"	15	42	TOP	24	1.438	0.953	6500	97.1
6.52"	15	42	MIDDLE	24	2.970	1	5920	88.4
5.44"	9	42	TOP	24	1.826	0.986	6545	97.7
5.11"	9	42	MIDDLE	24	1.721	0.978	6170	92.1
5.93"	15	53	TOP	24	1.997	1	6450	96.3
4.68"	15	53	MIDDLE	24	1.576	0.966	6025	89.9
5.73"	9	53	TOP	24	1.929	0.994	6590	98.4
5.14"	9	53	MIDDLE	24	1.731	0.978	5930	88.5
5.44"	15	65	MIDDLE	24	1.832	0.987	6340	94.6
5.61"	9	65	TOP	24	1.889	0.991	6280	93.7
5.19"	9	65	MIDDLE	24	1.747	0.98	6420	95.8
5.71"	15	75	TOP	24	1.922	0.994	5910	88.2
5.04"	15	75	MIDDLE	24	1.697	0.976	6055	90.4
5.42"	9	75	TOP	24	1.825	0.986	6645	99.2
5.42"	9	75	MIDDLE	24	1.825	0.986	6350	94.8
5.48"	15	85	TOP	24	1.845	0.988	6390	95.4
5.58"	15	85	MIDDLE	24	1.879	0.99	6345	94.7
6.54"	9	85	TOP	24	2.202	1	6525	97.4
5.97"	9	85	MIDDLE	24	2.010	1	6385	95.3
5.68"	15	96	TOP	24	1.906	0.992	5640	84.2
5.03"	15	96	MIDDLE	24	1.694	0.975	6195	92.5
5.61"	9	96	MIDDLE	24	1.889	0.991	6380	95.2
5.09"	15	107	MIDDLE	24	1.714	0.977	5925	88.4
3.96"	9	107	TOP	24	1.333	0.94	6010	89.7
5.14"	9	107	MIDDLE	24	1.731	0.978	6355	94.9
5.56"	15	117	TOP	24	1.872	0.99	5960	89.0
4.43"	15	117	MIDDLE	24	1.492	0.959	6120	91.3
3.94"	9	117	TOP	24	1.327	0.939	6020	89.9
4.02"	9	117	MIDDLE	24	1.354	0.942	6175	92.2

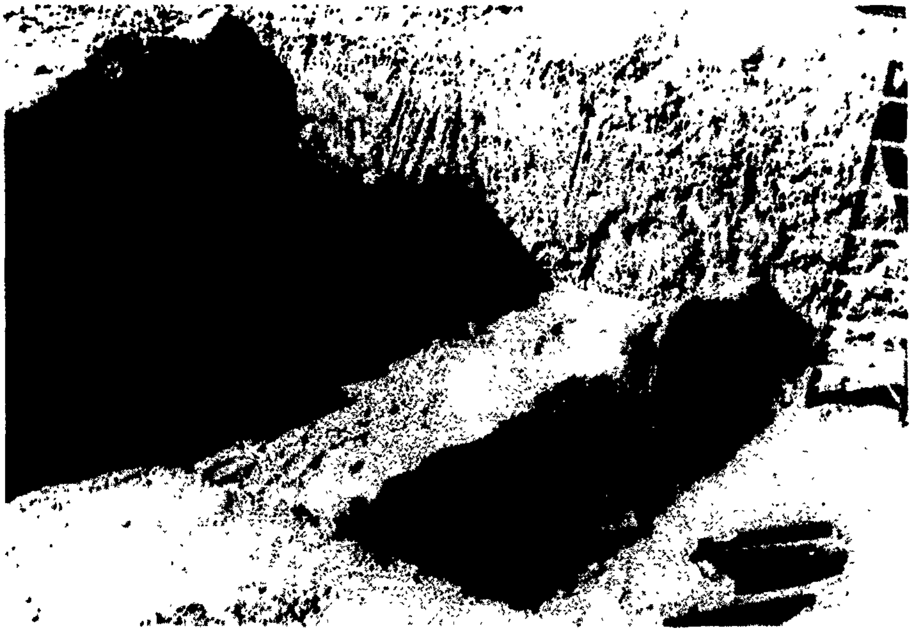


Fig. 94--Photograph of the Excavated Pit

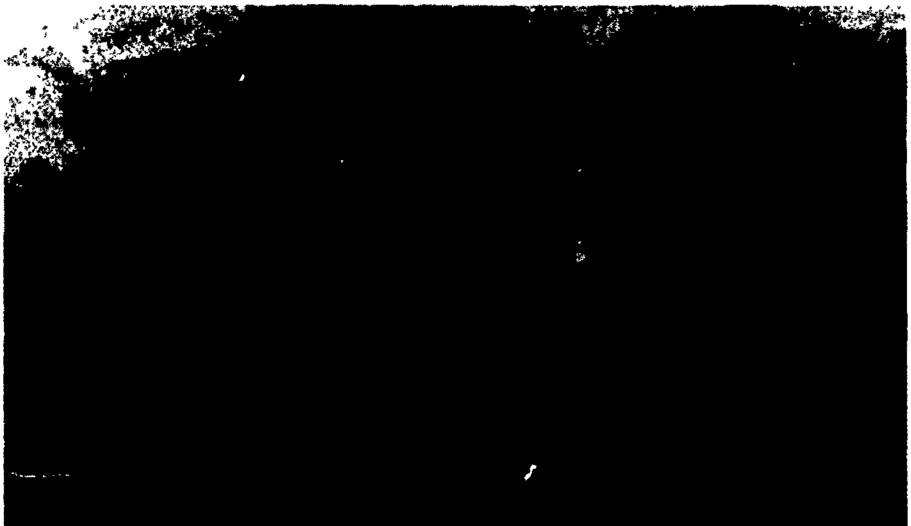


Fig. 95--Picture of Steel Beams with Spanning Steel Bars

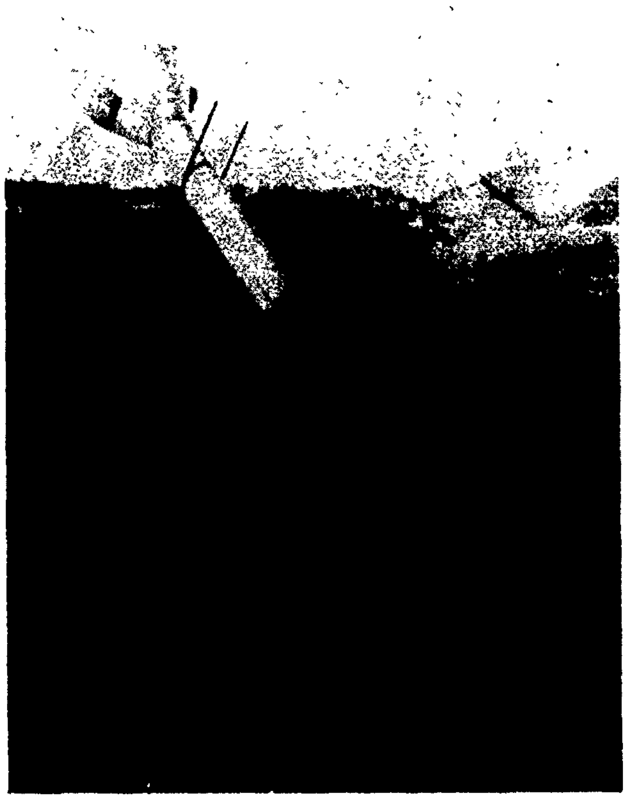


Fig. 96--Photograph of the Inclined Tremie Pipe

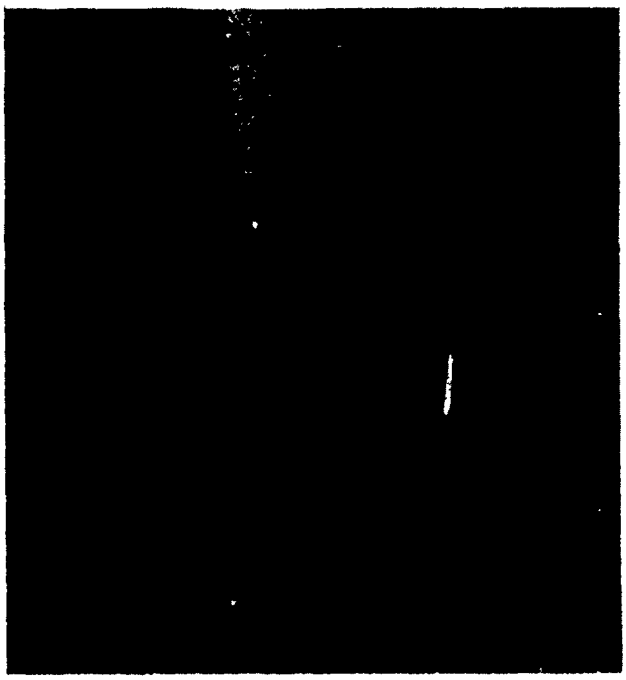


Fig. 97--Photograph Showing the End Plug

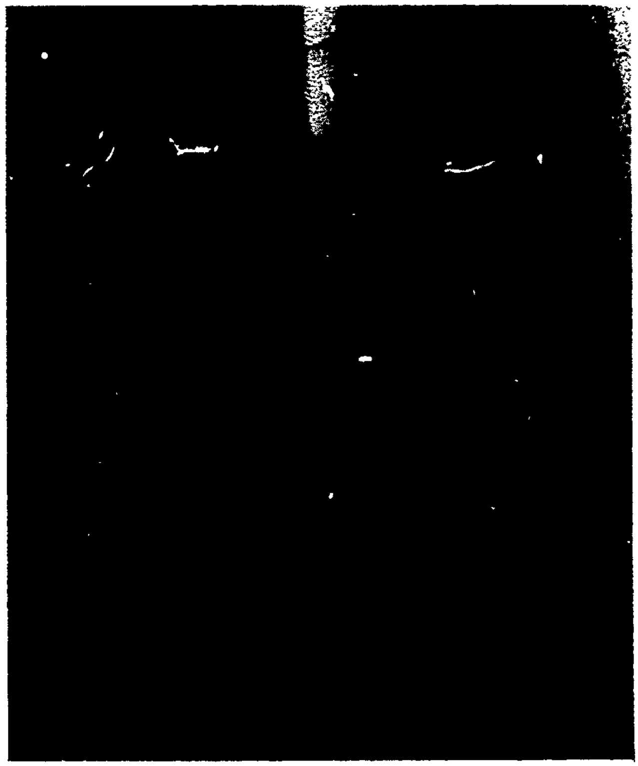


Fig. 98--Picture of a Completed Slab Before Flooding the Pit

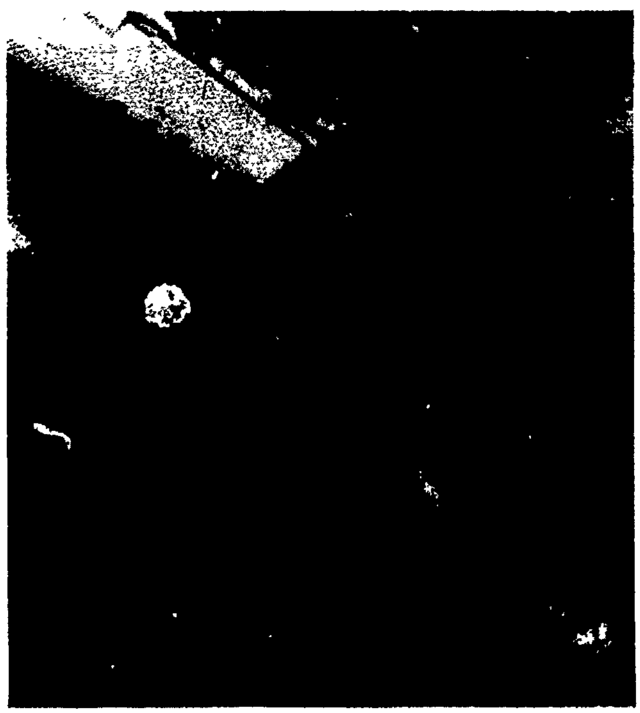


Fig. 99--Photograph of Concrete Casting

Table 43. Unit Weight Values along the K-FIELD Slab

K-FIELD				AGE,	DENSITY, PCF		% DENSITY	% OF
	COORDINATES		DESCRIPTION		UNCUT	CUT	INCREASE	CONTROL
CORE #	X, FT.	Y, FT.		DAYS			CUT/UNCUT	DENSITIES
CONTROL			(NOT MUCH AIR)	27	145.9			100.0
A TOP	4.3	3	12"	27	142.6	142.7	0.1	97.8
A BOT				27		142.5	0.0	97.7
O TOP	8.3	3	10.5", HIT MUD	27	142.9	143.4	0.3	98.3
O BOT				27		144.7	1.2	99.2
G TOP	1.5	3.5	0.25" LAITANCE, 1.5"	27	139.5	143.4	2.7	98.3
			MORTAR, 5" CONC.	27				
E TOP	4.3	7	11"	27	145.1	145.2	0.1	99.6
E BOT				27		145.2	0.1	99.6
F TOP	1.2	7	10", HIT MUD	27	144.4	144.3	-0.1	98.9
F BOT				27		144.7	0.2	99.2
H	3	9	12"	27	145	144.8	-0.2	99.2
I TOP	6.3	9	12"	27	144.9	144.8	0.0	99.3
I BOT				27		145.1	0.1	99.5
C TOP	4.3	11	12"	27	145.1	144.6	-0.4	99.1
C BOT				27		145.6	0.3	99.8
D TOP	1.3	11	10"	27	144.4	144.7	0.2	99.2
D BOT				27		144.8	0.3	99.3
J TOP	7.5	13.5	8", HIT GRAVEL	27	142.9	143.7	0.6	98.5
J BOT				27		143.6	0.5	98.5
K TOP	3	13.5	12", HIT MUD	27	144.5	144.2	-0.2	98.8
K BOT				27		145.4	0.6	99.7
L TOP	3	16.5	0.75" LAITANCE	27	142.1	143.9	1.2	98.6
L BOT			11" CONC.	27		145.0	2.1	99.4
M	3	20	0.5" LAITANCE	27	137.8	143.1	3.9	98.1
			3.5" SEG. 5" CONC.	27				
N TOP	2.5	20	0.5" LAITANCE	27	139.8	142.8	2.1	97.9
N BOT			3.5" SEG. 8" CONC.	27		145.6	4.2	99.8
B TOP	5	20	0.5" LAITANCE, 3"	27	139.4	143.0	2.6	98.0
B BOT			SEG., 7.5" CONC.	27		145.0	4.0	99.4

Table 44. Compressive Strength Results along the K-FIELD Slab

K-FIELD								
	COORDINATES		AGE,	LENGTH,		ADJ.	F'c	% CONT.
CORE #	X, FT.	Y, FT.	DAYS	IN.	L/D	FACTOR	PSI	F'c
7 CONT'S			29				8100	100.0
A TOP	4.3	3	29	5.55	1.869	0.989	6430	79.4
A BOT			29	5.44	1.832	0.987	5385	66.5
O TOP	8.3	3	29	4.9	1.65	0.972	5895	72.8
O BOT			29	4.96	1.67	0.974	6185	76.4
G TOP	1.5	3.5	29	3.7	1.246	0.929	5285	65.2
E TOP	4.3	7	29	5.39	1.815	0.985	8055	99.4
E BOT			29	5.2	1.751	0.980	7785	96.1
F TOP	1.2	7	29	4.15	1.397	0.948	8205	101.3
F BOT			29	4.19	1.411	0.949	7455	92.0
H	3	9	29	5.18	1.744	0.979	7640	94.3
I TOP	6.3	9	29	5.53	1.862	0.989	7885	97.3
I BOT			29	5.62	1.892	0.991	8275	102.2
C TOP	4.3	11	29	5.5	1.852	0.988	7880	97.3
C BOT			29	5.58	1.879	0.990	8240	101.7
D TOP	1.3	11	29	4.78	1.609	0.969	8145	100.6
D BOT			29	4.75	1.599	0.968	7445	91.9
J TOP	7.5	13.5	29	3.61	1.215	0.922	6865	84.8
J BOT			29	3.71	1.249	0.930	7115	87.8
K TOP	3	13.5	29	5.56	1.872	0.990	7860	97.0
K BOT			29	5.08	1.71	0.977	7830	96.7
L TOP	3	16.5	29	5.08	1.71	0.977	6685	82.5
L BOT			29	4.88	1.643	0.971	7140	88.1
M	3	20	29	4.58	1.542	0.963	4120	50.9
N TOP	2.5	20	29	4.15	1.397	0.948	4215	52.0
N BOT			29	4.3	1.448	0.954	5725	70.7
B TOP	5	20	29	3.92	1.32	0.938	4280	52.8
B BOT			29	3.84	1.293	0.935	4520	55.8

Table 45. Unit Weight Values along the MB-FIELD Slab

MB-FIELD					DENSITY, PCF		% DENSITY	% OF
	COORDINATES		DESCRIPTION	AGE,	UNCUT	CUT	INCREASE	CONTROL
CORE #	X, FT.	Y, FT.		DAYS			CUT/UNCUT	DENSITIES
CONTROL			(MUCH AIR)	27	145.7			100.0
G TOP	8.5	2	12", HIT MUD	27	141.1	140.1	-0.7	96.2
G BOT				27		142.5	1.0	97.8
H	10	2	0.25" LAITANCE 4.5" CONC., HIT P.G.	27	138.8	139.1	0.2	95.5
J	6.3	4.5	3" REPAIR, 5.5" MB BROKE @ BOND		144.6	145.1	0.4	99.6
F TOP	8.5	6	11", HIT MUD	27	145.1	143.6	-1.0	98.6
F BOT				27		147.3	1.5	101.1
I TOP	4.3	6.5	2.5" REPAIR, 9.5" MB	27	143.4	142.9	-0.3	98.1
I BOT			BROKE @ BOND, VOIDS	27		144.7	0.9	99.3
A TOP	1.5	8.5	12"	27	146.3	143.4	-2.0	98.4
A BOT				27		149.2	2.0	102.4
E TOP	8.5	10	9"	27	144.3	142.5	-1.3	97.8
E BOT				27		147.1	1.9	101.0
B TOP	4.3	10	9.5"	27	144.1	143.0	-0.8	98.1
B BOT				27		145.3	0.8	99.7
K TOP	5.8	13	12"	27	144	143.1	-0.6	98.2
K BOT				27		145.0	0.7	99.5
C TOP	4 3	14	11.5"	27	143.3	141.0	-1.6	96.8
C BOT				27		146.3	2.0	100.4
D	8.5	14	11"	27	142.2	141.3	-0.6	97.0
L TOP	4.3	18	12"	27	142.4	140.5	-1.3	96.5
L BOT				27		145.7	2.4	100.1
M	4.3	20.5	1" LAITANCE, 5" CONC., HIT MUD, AIR	27 27	134.8	141.3	4.8	97.0
N	5	20.5	1" LAITANCE, 7" CONC., HIT MUD, AIR	27 27	135.9	140.8	3.6	96.7

Table 46. Compressive Strength Results along the MB-FIELD Slab

MB-FIELD								
	COORDINATES		AGE,	LENGTH,		ADJ.	F'c,	% CONT.
CORE #	X, FT.	Y, FT.	DAYS	IN.	L/D	FACTOR	PSI	F'c
7 CONT'S			29				7100	100.0
G TOP	8.5	2	29	5.7	1.919	0.994	6820	96.1
G BOT			28	5.63	1.896	0.992	4650	AIR VOID
H	10	2	29	4.8	1.616	0.969	6845	96.4
J	6.3	4.5	29	4.6	1.549	0.964	6780	95.5
F TOP	8.5	6	28	4.51	1.519	0.961	7080	99.7
F BOT			29	4.33	1.458	0.955	6480	91.3
I TOP	4.3	6.5	29	5.54	1.865	0.989	4670	AIR VOID
I BOT			28	4.4	1.481	0.958	5335	AIR VOID
A TOP	1.5	8.5	28	5.08	1.71	0.977	6570	92.5
A BOT			29	5.33	1.795	0.984	6805	95.8
E TOP	8.5	10	29	4.08	1.374	0.945	6875	96.8
E BOT			28	5.23	1.761	0.981	7165	100.9
B BOT			28	4.62	1.556	0.964	6810	95.9
K TOP	5.8	13	28	5.9	1.967	0.999	6765	95.3
K BOT			28	5.96	2.001	1.000	7160	100.8
C TOP	4.3	14	29	5.46	1.838	0.987	6545	92.2
C BOT			28	5.34	1.798	0.984	6290	88.6
D TOP	8.5	14	29	5.2	1.751	0.980	6455	90.9
D BOT			29	4.17	1.404	0.948	6480	91.3
L TOP	4.3	18	28	5.76	1.939	0.995	6390	90.0
L BOT			29	5.7	1.919	0.994	6360	89.6
M	4.3	20.5	29	3.92	1.32	0.938	6520	91.8
N	5	20.5	29	4.25	1.431	0.952	6475	91.2

Appendix F - Development and Evaluation of Stiff Concretes

Table 47. Mix Proportions and Properties of Trial Concretes

TRIAL MIXTURES	23	23 A	24	24 A	25	25 A	26	26 A
CEMENT, PCY	741	744	750	749	749	740	752	752
SILICA FUME, % CEM.	15	15	15	15	15	15	15	15
FLY ASH, % CEM.	0	0	0	0	0	0	0	0
SLAG, % 0F CEM.	0	0	0	0	0	0	0	0
TOTAL CM, PCY	852	856	862	862	861	851	865	865
W/CM	0.31	0.32	0.3	0.32	0.35	0.34	0.34	0.33
SAND % OF AGG. VOL.	46	46	46	46	46	46	46	46
HRWRA	--->	--->	SIKAFF86		<---	<---	<---	<---
FL. OZ./100# CM	32	37	30	34	38	38	38	38
FIBERS					POLYETHYLENE		STEEL	STEEL
% BY VOLUME					0.55	0.5	0.75	0.75
CACL2, % OF CM	0	2	0	1.5	1.25	1 -	1	1
AWA	PROTEX	<<---	MASTER BUILDERS		PROTEX	MASTER BUILDERS		
% OF CM	0.85	0.75	1.75	1.7	0.75-	1.5	1.5	1.5
DE-AIR, % OF CM	0.2	0.2	0.2	0.2	0.2	0.2+	0.2	0.2
UNIT WT., PCF	148.8	148.6	150.1	148.5	148	147	150.6	150.8
AIR VOL., %	1	1	1	1	1	1.5	1	1.25
MIX + ADJUST. MIN.	20	15	20	20	60	25	20	20
SLUMP, IN. INITIAL	4.5	2.25	4.5	2.5	1	1.25	3	1.75
+ 30 MIN.	3.75	1.5	3.5	2		1		0.75
+ 60 MIN.		1		1.75		0.5		0.5
+ 90 MIN.		0.75		1.25				
FLOW, IN. INITIAL	11.4	10.75	11.75	11.75	10	12	12	10.5
+30 MIN.	11.25	10.25	11.5	10.75		10		9.75
+ 60 MIN.		9.5		10.5		9.25		9.5
+ 90 MIN.		9.5		·10.5				9
WASH OUT	#1= .05	#3= .34	#1= .05	#3= .18		#3= .35		#3= .21
	#3= .24	#5= .53	#2= .24	#5= .39		#5= .64		#5= .34
	#6= .63	#10= 1	#3= .48	#10= .75		#10= 1		#10=.93
COMMENTS	STICKY	<---	<---	<---	W/.33	NOFIBER	<---	<---
	V. COHE.	USE	<---	STICKY	F=9	F= 13.5	F=14.75	F= 13.2
	V. STIFF	0.33	<---	PLASTIC	PLASTIC	PLAST.	<---+	V. STIFF
	SLOW	LOWER	<---	SLOW	NO	NICE	V. NICE	V. NICE
	FLOW	CACL2	<---	FLOW	FLOW		COHES.+	<---
SETTING. HRS.	48	8.5/10	48	11/12.5	<12	6/7.25		7.5/8.5

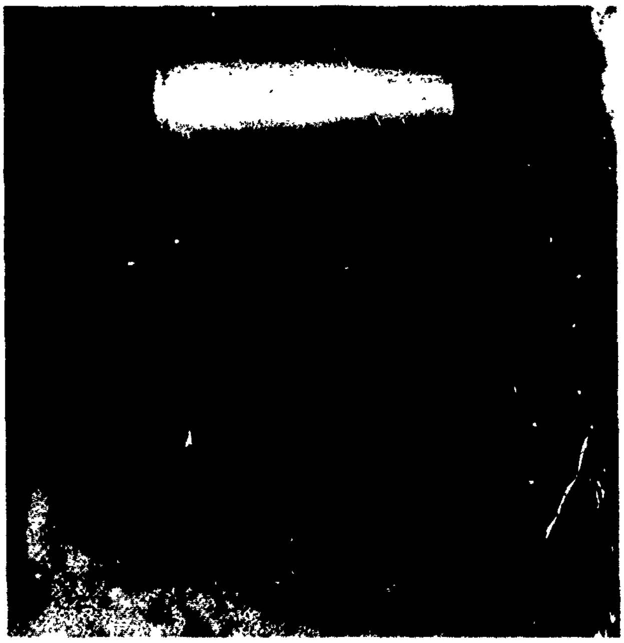


Fig. 100--Photograph of a Trial Stiff Concrete Slab after Casting in Water

Fig. 101--Picture of a Trial Stiff Concrete Slab after Underwater Compaction

Fig. 102--Photograph of the Large Concrete Roller inside the Placement Box

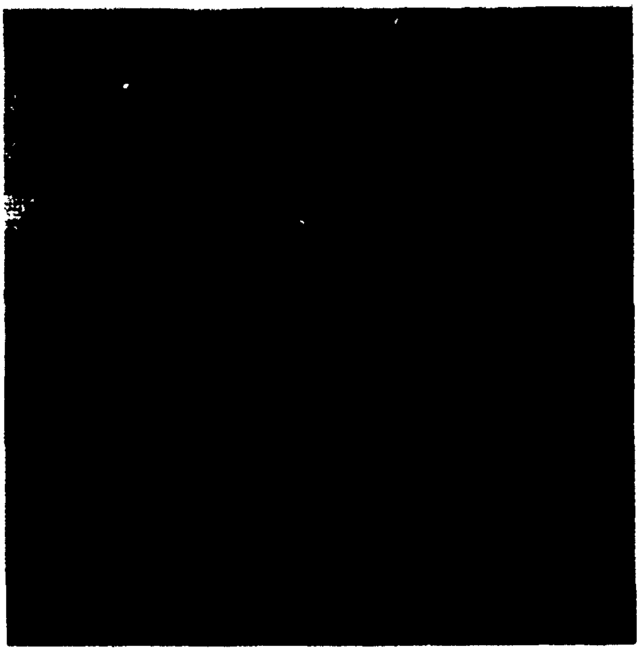


Fig. 103--Picture of the Bottom-dumping Skip

Fig. 104--Photograph of Skip during Underwater Placement

Table 48. Unit Weight Results along SLAB NO. 1

SLAB NO. 1 NO. OF PASSES 2 MEDIUM + 24 LARGE								
CORE	COORDINATES		CUT LENGTH,	AGE,	UNCUT	CUT	% DENSITY INCREASE	% OF AVG. CONTROL
	X, IN.	Y, IN.	IN.	DAYS	CORE DENSITY, PCF		CUT/UNCUT	DENSITIES
CONTROL I				106	148.6			100
CONTROL II				106	148.1			100
1A	9	27	3.3	106	147.8	147.9	0.06	99.7
1B	14	27	4.3	106	147.1	147.6	0.36	99.5
1C	20	27	4	106	147.5	147.7	0.11	99.6
1I	10	33	2.7	106	147.6	148.1	0.33	99.8
1D	10	38	4.1	106	147.6	148.0	0.29	99.8
1E	15	38	4.1	106	147.5	147.6	0.03	99.5
1F	21	38	3.4	106	148.0	148.3	0.21	99.9
1G	12	46	3.7	106	147.3	148.0	0.50	99.7
1H	18	46	2	106	148.6	148.9	0.20	100.4

Table 49. Compressive Strength Values along SLAB NO. 1

SLAB NO. 1 NO. OF PASSES 2 MEDIUM + 24 LARGE								
CORE	COORDINATES		AGE,	CAPPED	L/D	ADJ.	F'c,	% CONT.
	X, IN.	Y, IN.	DAYS	L, IN.		FACTOR	PSI	A AND B
CONTROL I			109				11280	100
CONTROL II			109				10830	100
1B	14	27	109	4.56	1.629	0.970	9505	86.0
1C	20	27	109	4.16	1.486	0.958	9545	86.3
1I	10	33	109	2.98	1.06	0.884	8925	80.7
1D	10	38	109	4.38	1.566	0.965	9550	86.4
1F	21	38	109	3.64	1.3	0.936	9505	86.0
1G	12	46	109	3.89	1.389	0.947	9410	85.1

Table 50. Bond Strength Results along SLAB NO. 1

SLAB NO. 1 NO. OF PASSES 2 MEDIUM + 24 LARGE AGE: 107 DAYS						
CUT CORE DESCRIPTIONS	BONDED MAT'S	COORDINATES		BOND STRENGTH, PSI	% OF MIX	COMMENTS
		X, IN.	Y, IN.			
2.3" OLD, 4.2" NEW	NEW / OLD	9	27	295	66 OLD, 52 NEW	@BOND
2.3" OLD, 4.3" NEW	NEW / OLD	20	27	260	63 OLD	@BOND
2.5" OLD, 4.5" NEW	NEW / OLD	15	38	295	65 OLD, 53 NEW	@BOND
4.1" NEW	NEW/NEW	9	27	565	----	@BOND
4.2" NEW	NEW/NEW	15	38	560	----	@BOND
2.3" OLD	OLD/OLD	9	27	450	----	JAGGED
3.2" OLD	OLD/OLD	20	27	410	----	JAGGED
2.3" OLD	OLD/OLD	15	38	455	----	JAGGED
2.9" OLD	OLD/OLD	21	38	470	----	JAGGED

Table 51. Unit Weight Results along SLAB NO. 2

SLAB NO. 2 NO. OF PASSES 2 MEDIUM + 4 LARGE								
CORE	COORDINATES		CUT LENGTH,	AGE,	UNCUT	CUT	% DENSITY INCREASE	% OF AVG. CONTROL
					CORE DENSITY			
	X, IN.	Y, IN.	IN.	DAYS	PCF		CUT/UNCUT	DENSITIES
CONT. TOP				104	149.1			100
CONT. BOTTOM				104	149.1			100
2A	23	28	3.9	104	147.6	147.8	0.14	99.1
2B	18	29	3.9	104	147.8	147.9	0.07	99.2
2C	12	29	3.6	104	147.7	147.9	0.12	99.2
2D	9	37	3.6	104	147.1	147.4	0.25	98.9
2E	15	37	3.9	104	147.1	147.5	0.22	98.9
2F	19	37	4	104	147.3	147.6	0.16	99.0
2G	22	40	3.9	104	147.3	147.5	0.15	99.0

Table 52. Compressive Strength Results along SLAB NO. 2

SLAB NO. 2 NO. OF PASSES 2 MEDIUM + 4 LARGE								
CORE	COORDINATES		AGE,	CAPPED	L/D	ADJ.	F'c,	% CONT.
	X, IN.	Y, IN.	DAYS	L, IN.		FACTOR	PSI	A AND B
CONT. TOP			104				11600	100
CONT. BOTTOM			104				11440	100
2A	23	28	105	4.13	1.475	0.957	10230	88.8
2B	18	29	105	4.15	1.482	0.958	10790	93.7
2C	12	29	105	3.83	1.368	0.944	10080	87.5
2D	9	37	105	3.83	1.368	0.944	10000	86.8
2F	19	37	105	4.25	1.518	0.961	9750	84.6

Table 53. Bond Strength Results along SLAB NO. 2

SLAB NO. 2 NO. OF PASSES		2 MEDIUM + 4 LARGE				AGE: 104 DAYS
CUT CORE DESCRIPTIONS	BONDED MAT'S	COORDINATES X, IN.	Y, IN.	BOND STRENGTH, PSI	% OF MIX	COMMENTS
3.1" OLD, 4.5" NEW	NEW / OLD	23	28	235	48 OLD	@ BOND, FLAT
3.1" OLD, 4.3" NEW	NEW / OLD	18	29	285	63 OLD	@ BOND, FLAT
3" OLD, 4.2" NEW	NEW / OLD	12	29	260	59 OLD	@ BOND, FLAT
3" OLD, 4.1" NEW	NEW / OLD	9	37	305	----	@ BOND, FLAT
3.2" OLD, 4.6" NEW	NEW / OLD	15	37	280	54 OLD	@ BOND, FLAT
3.2" OLD, 4.6" NEW	NEW / OLD	19	37	345	64 OLD	@ BOND, FLAT
3.2" OLD, 4.8" NEW	NEW / OLD	22	40	245	46 OLD	@ BOND, FLAT
4.5" NEW	NEW/NEW	19	37	540	----	ANGULAR
4.6" NEW	NEW/NEW	22	40	530	----	ANGULAR
3" OLD	OLD/OLD	23	28	485	----	JAGGED
3" OLD	OLD/OLD	18	29	455	----	JAGGED
3" OLD	OLD/OLD	12	29	440	----	JAGGED
3.1" OLD	OLD/OLD	15	37	515	----	JAGGED
3.2" OLD	OLD/OLD	19	37	535	----	JAGGED
3" OLD	OLD/OLD	22	40	530	----	JAGGED

Table 54. Unit Weight Results along SLAB NO. 3

SLAB NO. 3 NO. OF PASSES 4 LARGE								
CORE	COORDINATES X, IN.	Y, IN.	CUT LENGTH, IN.	AGE, DAYS	UNCUT CORE DENSITY, PCF	CUT	% DENSITY INCREASE CUT/UNCUT	% OF AVG. CONTROL DENSITIES
CONT. TOP				107	148.3			100
CONT. BOTTOM				107	148.4			100
3A	10	28	3.3	110	146.7	147.2	0.36	99.3
3B	13.5	32	4.3	110	146.3	146.5	0.13	98.8
3C	17	34	4	110	147.4	147.5	0.10	99.4
3D	11.5	37	2.7	110	147.2	147.3	0.12	99.3
3E	15.5	37	4.1	110	146.9	147.2	0.20	99.2
3F	16	43	4.1	110	147.2	147.4	0.17	99.4

Table 55. Compressive Strength Results along SLAB NO. 3

SLAB NO. 3								
NO. OF PASSES			4 LARGE					
CORE	COORDINATES		AGE,	CAPPED	L/D	ADJ.	F'c,	% CONT.
	X, IN.	Y, IN.	DAYS	L, IN.		FACTOR	PSI	A AND B
CONT. TOP			108				11510	100
CONT. BOTTOM			108				11300	100
OLD			108				11335	
3B	13.5	32	108	3.02	1.079	0.889	9530	83.6
3C	17	34	108	3.23	1.154	0.907	10500	92.1
3D	11.5	37	108	2.91	1.039	0.879	9710	85.1
3E	15.5	37	108	3.51	1.254	0.931	9220	80.8
3F	16	43	108	3.3	1.179	0.913	10055	88.2

Table 56. Bond Strength Results along SLAB NO. 3

SLAB NO. 3						
NO. OF PASSES		4 LARGE				AGE: 107 DAYS
CUT CORE DESCRIPTIONS	BONDED MAT'S	COORDINATES		BOND STRENGTH, PSI	% OF MIX	COMMENTS
		X, IN.	Y, IN.			
3" OLD, 2" NEW	NEW / OLD	10	28	285	56 OLD	@ BOND, FLAT
3" OLD, 3.3" NEW	NEW / OLD	13.5	32	250	47 OLD	@ BOND, FLAT
3" OLD, 4" NEW	NEW / OLD	17	34	295	51 OLD	@ BOND, FLAT
3" OLD, 3.3" NEW	NEW / OLD	11.5	37	270	56 OLD	@ BOND, FLAT
3" OLD, 4" NEW	NEW / OLD	15.5	37	270	45 OLD	@ BOND, FLAT
3" OLD, 3.8" NEW	NEW / OLD	16	43	280	50 OLD	@ BOND, FLAT
3" OLD	OLD/OLD	10	28	505	----	JAGGED
3" OLD	OLD/OLD	13.5	32	535	----	JAGGED
3" OLD	OLD/OLD	17	34	575	----	JAGGED
3.1" OLD	OLD/OLD	11.5	37	480	----	JAGGED
3.2" OLD	OLD/OLD	15.5	37	600	----	JAGGED
3" OLD	OLD/OLD	16	43	565	----	JAGGED

Appendix G - Notation

W/CM	Water-to-Cementitious Material Ratio
AWA	Anti-washout Admixture
HRWRA	High Range Water-reducing Admixture (Superplasticizer)
WRA	Water-reducing Admixture
AEA	Air-entraining Admixture
(Dimensions)	Length x Width x Depth
CONTROL	Control Fluid Concrete without AWA
HSFLPRO	High Silica Fume Low Protex, Fluid Concrete with Protex AWA
MSFMPRO	Medium Silica Fume Medium Protex, Fluid Concrete with Protex AWA
LSFHPRO	Low Silica Fume High Protex, Fluid Concrete with Protex AWA
MSFMMB	Medium Silica Fume Medium Master Builders, Fluid Concrete with Master Builders AWA
SLAGMPRO	Slag Medium Protex, Fluid Concrete with Protex AWA
FAMPRO	Fly Ash Medium Protex, Fluid Concrete with Protex AWA
FA-NOSF	Fly Ash without Silica Fume, Fluid Concrete with Protex AWA
RESCON	Fluid Concrete Mixture with Rescon AWA
KELCO	Fluid Concrete Mixture with Kelco AWA
Z10-A	Fluid Concrete Mixture with Z10-A AWA
KT-1/2	Modified KELCO Concretes for Casting Reinforced Beam No. 1 and 2
K-FIELD	Modified KELCO Concrete for Casting Large Slab in the Field
MB-FIELD	Modified MSFMMB Concrete for Casting Large Slab in the Field
STIFF-PRO	Stiff-Protex, Stiff Concrete with Protex AWA
STIFF-M.B.	Stiff-Master Builders, Stiff Concrete with Master Builders AWA
STIFF-STEEL	Stiff Concrete with Steel Fibers and Master Builders AWA
STIFF-POLY	Stiff Concrete with Polyethylene Fibers and Master Builders AWA